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Bolometric measurement of Molybdenum half-life

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Double Beta Decay - 1

Rare transition among isobaric elements:

$$(A, Z) \Longrightarrow (A, Z \pm 2)$$

- 2νDBD: useful for testing nuclear models

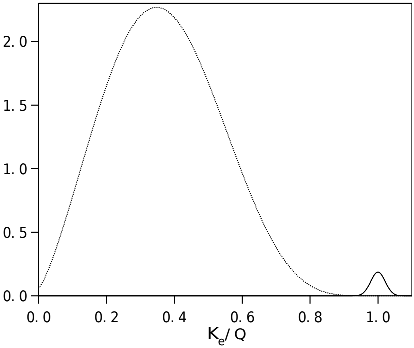
$$\frac{1}{T_{1/2}^{2\nu}} = G^{2\nu}(Q, Z)|M^{2\nu}|^2$$

  $G^{2\nu}(Q, Z) \Rightarrow$ phase space of outgoing leptons
  $M^{2\nu} \Rightarrow$ Nuclear Matrix Element

- 0νDBD: fundamental physics, if observed would prove the Majorana nature of neutrinos.
  The measurement of $T_{1/2}^{0\nu}$ would be a measurement of neutrino mass.

Large half-lives $T_{1/2} \approx 10^{18} - 10^{21}$ years.

- Only emitters for which the single beta decay is forbidden are under study.
- Due to the rarity of the process high sensitive detectors are required
- Sensitivity for spotting 0νDBD peak over a background B



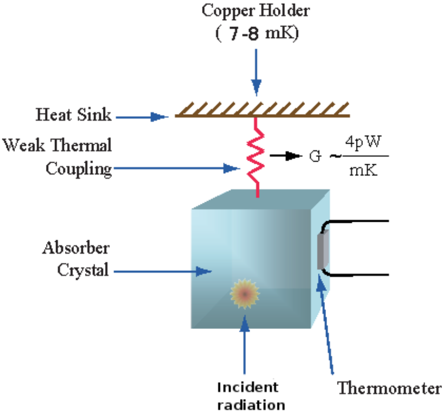
$$S^{0\nu} = \log 2 T \epsilon \frac{N_{\beta\beta}}{n_B} \propto \epsilon \sqrt{\frac{MT}{B\Delta}}$$

Isotope	Q-value [keV]	Isotopic abundance [%]
^{100}Mo	3035	9.63

Detectors which convert the released energy into heat

Components:

- Absorber: detector's active volume. The interaction causes its warm-up.
- Thermal link which keeps a constant working temperature.
- Thermal sensor: sensor which convert the thermal pulse into an electric one.



Particle interactions cause the pulse formation

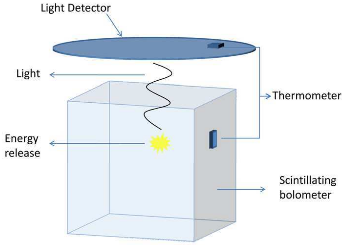
$$\Delta T(t) = \frac{E}{C} e^{-\frac{t}{\tau}} \qquad \tau = C/G$$

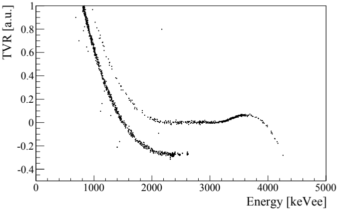
- C contributions: lattice, electronic and magnetic. The choice of dielectric-diamagnetic absorbers makes the lattice contribution the only effective at very low temperature.
- Debye law: $C \sim (T/\Theta_D)^3 \quad T \ll \Theta_D$, High resolution at low T
- The absorbers may contain the source $\Rightarrow$ high efficiency.
- Absorbers mass up to ∼kg. Bolometers can be made of many absorbers, up to ∼1ton $\Rightarrow$ high sensitivity
- $\tau \sim 1s$: slow detectors.

Scintillating bolometers

Double read-out: heat signal and light signal

- A small fraction of the released energy is emitted as photons.
- Due to distinct specific energy-loss this fraction is different for α and β/γ radiations.
- α-events rejection allows to increase the sensitivity.
- In scintillating crystals this event discrimination is possibile by studying the (thermal) pulse shape.



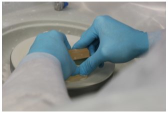


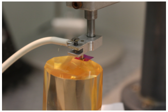
Experimental setup - Crystals

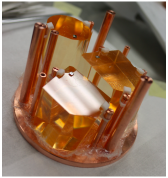
I arranged up three crystals made of $\mathrm{ZnMoO_4}$ as bolometers

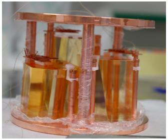
Preparation:

- Surface cleaning
- Gluing of thermal sensors and heaters
- Mounting in copper frame
- Wiring
- No light detectors, I totally relied on pulse shape discrimination









Crystal	Mass (g)	DBD Emitters $^{100}\mathrm{Mo}$
$\mathrm{ZnMoO_4} - 1$	235.2 ± 0.1	$(6.056 \pm 0.003) \times 10^{22}$
$\mathrm{ZnMoO_4} - 2$	247.0 ± 0.1	$(6.360 \pm 0.003) \times 10^{22}$
$\mathrm{ZnMoO_4} - 3$	328.8 ± 0.1	$(8.467 \pm 0.003) \times 10^{22}$

The thermal pulse is converted into a tension pulse

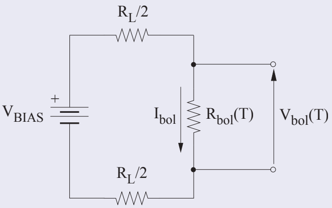
$R_{bol} \Rightarrow$ Thermal sensor
$R_L \Rightarrow$ Load resistance
$V_{BIAS} \Rightarrow$ Tunable voltage
$V_{bol} \Rightarrow$ Sampled signal

$R_L \gg R_{bol} \Rightarrow I_{bol} \approx$ const

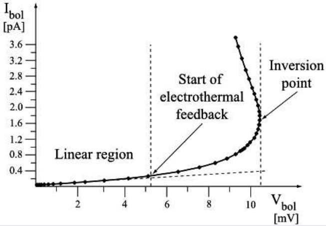
$$\frac{\mathrm{d}R}{R} = A\frac{\mathrm{d}T}{T}$$

$$\Delta V_{bol} \approx \frac{\Delta E}{CT} A\sqrt{PR_{bol}}$$

Circuit



Load curve



First level analysis

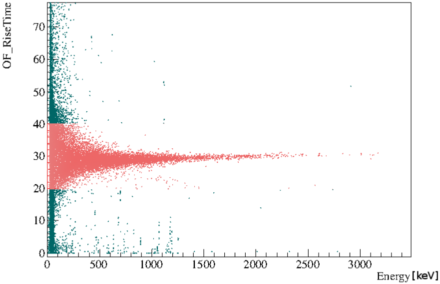
I applied many manipulation to the raw data in order to optimize the detector performance

- Optimum Filter: transfert function which maximizes the signal-to-noise ratio
- Stabilization: pulses amplitudes are corrected respect to thermal fluctuations
- Calibration
- Pulse shape analysis: since we are interested in the study of a continuum energy spectrum, I implemented a method to select "good" events with an energy-constant efficiency

Shape cuts

During 36.5 days of measurement some recorded events are to be rejected because due to not-properly shaped pulses, noise, pile-ups... The rejection (cut) directly affects the detection efficiency and thus the half-life calculation

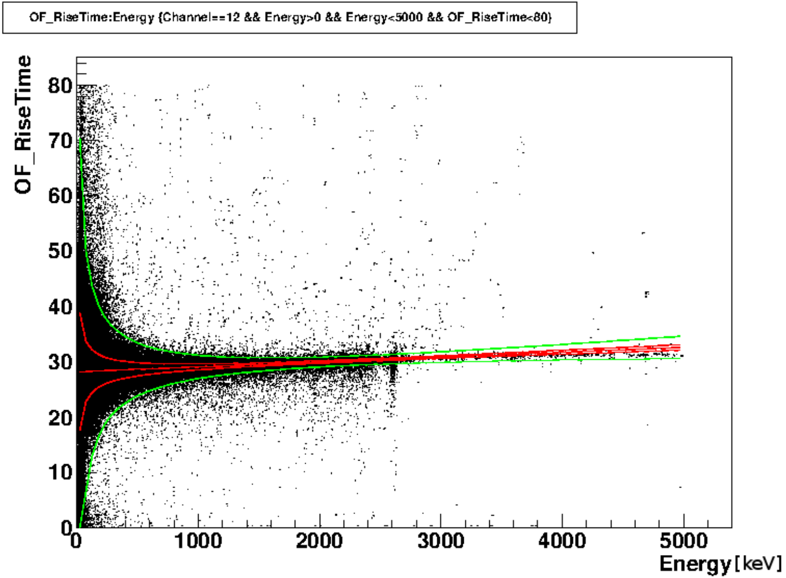
- "box" cuts $\Rightarrow$ energy-dependent efficiency



- Pulse shape linearization:

$$\hat{p}_j = \frac{p(E_j) - \bar{p}(E_j)}{sigma(E_j)} \qquad \hat{p}_j \text{ E-independent}$$

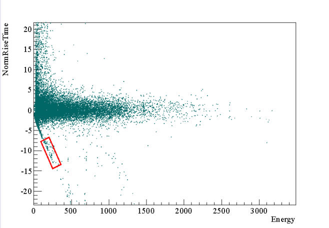
Shape cuts


OF_RiseTime:Energy {Channel==12 && Energy>0 && Energy<5000 && OF_RiseTime<80}
OF_RiseTime
80
70
60
50
40
30
20
10
0
0
1000
2000
3000
4000
5000
Energy [keV]

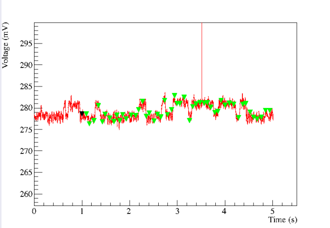
Shape cuts

Thanks to linearized shape parameters non-particle patterns are easily spotted

Linearized RiseTime



Triggered noise



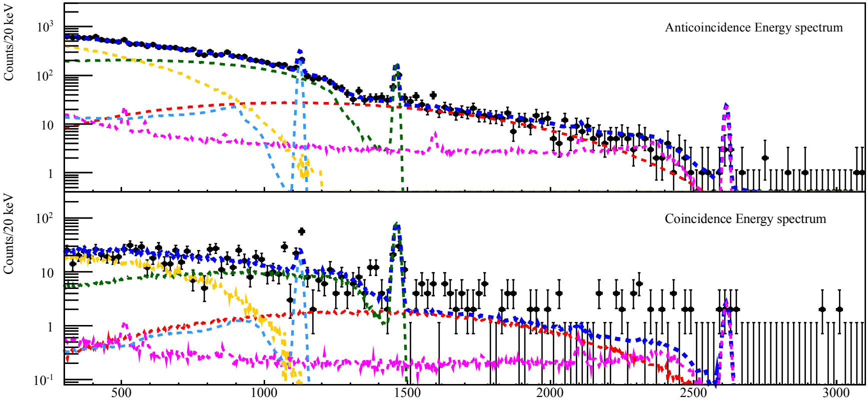
Background reconstruction - $T_{1/2}^{2\nu}$

The number of 2νDBD disintegration is computed by reconstructing the entire background

- The geometry has been simulated with Geant
- Background contributions (simulated):
  - $^{65}\mathrm{Zn}$ inside crystals
  - $^{210}\mathrm{Pb}$-$^{210}\mathrm{Bi}$ both as internal and external contamination
  - $^{208}\mathrm{Tl}$ external contamination due to $^{232}\mathrm{Th}$ in materials facing the detectors
  - $^{40}\mathrm{K}$ both internal and external due to environmental radioactivity
- Measured spectra have been split in single-crystal and double-crystal events
- I overlapped the simulated spectrum to the measured one by means of likelihood maximization

Background reconstruction - $T_{1/2}^{2\nu}$

$\text{bkg} = 2\nu + {}^{208}\text{Tl} + {}^{40}\text{K} + {}^{65}\text{Zn} + {}^{210}\text{Pb}-{}^{210}\text{Bi}$



First bolometric measurement of $^{100}\mathrm{Mo}$ half-life:

$$T_{1/2}^{2\nu} = (7.15 \pm 0.37(stat) \pm 0.66(syst)) \times 10^{18} \text{ years}$$

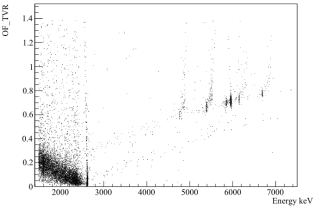
In agreement with the result obtained by NEMO[1] (the most accurate avaiable):

$$T_{1/2}^{2\nu} = (7.11 \pm 0.02(stat) \pm 0.54(syst)) \times 10^{18} \text{ years}$$

[1] R. Arnold *et al.*, First results of the search of neutrinoless double beta decay with the NEMO 3 detector, Phys.Rev.Lett. 2005

Sensitivity $T^{0\nu}_{1/2}$

Only one crystal showed the capability to discriminate α events by pulse shape.



I used this to calculate the sensitivity of an experiment based on 10Kg of $\mathrm{ZnMoO_4}$ with α rejection for 1 year exposure (CL 68%)

$$T^{0\nu}_{1/2} > 1.14 \times 10^{24} \text{ years}$$

A pure bolometric result would be

$$T^{0\nu}_{1/2} > 6.5 \times 10^{23} \text{ years}$$

Conclusion

- Independent confirmation of NEMO result with natural Mo (no enrichment!)
- Proved that $\mathrm{ZnMoO_4}$ crystals allow α-background rejection by means of pulse shape discrimination (though it requires further studies)