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Pulse Shape Analysis with scintillating bolometers

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12th Pisa Meeting on Advanced Detectors
La Biodola, Isola d'Elba (Italy)
May 20 - 26, 2012

Detectors for rare event searches

Considerable interest has always been devoted to the research of extremely **rare events** since they could give an insight into the existence of **new fundamental physics**.

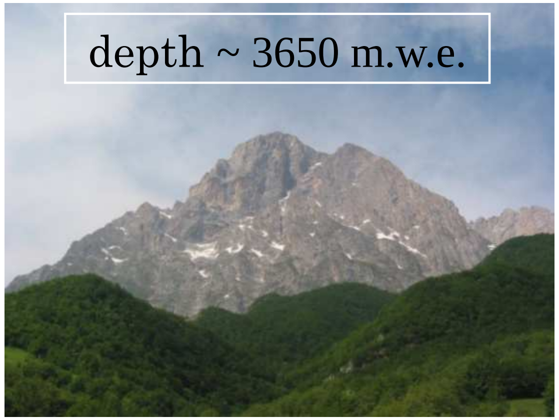
All the experiments aiming to study rare events require **low background** otherwise it could hide the searched signal.

Passive methods

- 'Huge' shielding for environmental radioactivity and selection of detector materials (γ, β, neutrons)
- Surface cleaning of materials (α)
- Underground (cosmic ray - μ)

Active methods

- Particle type identification in order to remove all the events that can mimic the event searched



Often both approaches

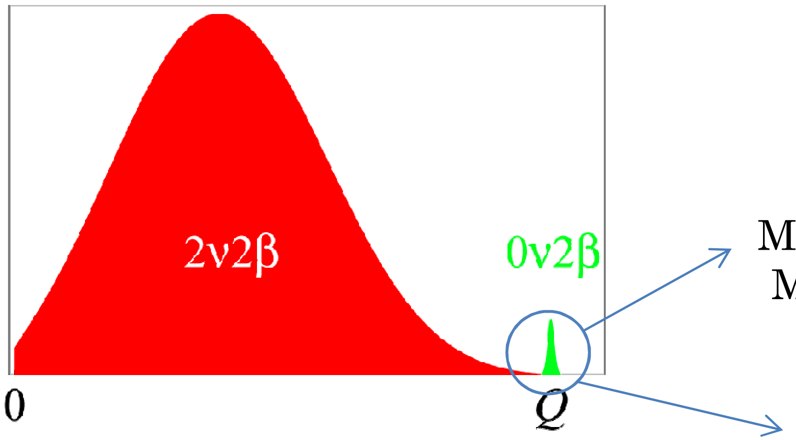
are required!!

Detectors for rare event searches

In the following I will focus on **neutrinoless Double Beta Decay** (0vDBD) experiments but similar remarks apply to many other rare events such as Dark Matter searches or rare alpha decays studies.

Neutrinoless Double Beta Decay (0vDBD)

$$(A, Z) \rightarrow (A, Z+2) + 2e^-$$



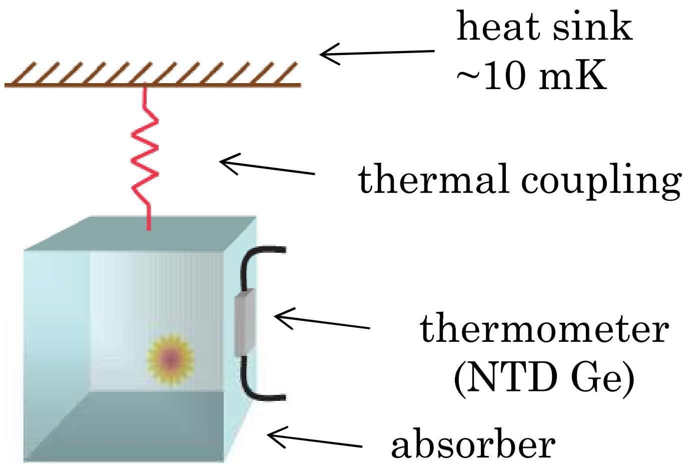
Neutrino:
Majorana particle
Massive particle

$Q_{\beta\beta}$ ~ 2-4 MeV
$T_{1/2} > 10^{24}$ years

The bolometric technique is one of the most promising approaches for rare events studies because:

- being solid state detectors bolometers allow easily to maximize the **detection efficiency** and **mass**;
- the **energy resolution** is among the best ever measured for massive solid state detectors (i.e. between 5 keV and 10 keV at 3 MeV);
- the **choice of the absorber material** allows to search 0vDBD for isotopes with high natural isotopic abundance and/or to maximize the isotopic abundance through enrichment.
- …

The bolometric technique: working principle



heat sink
~10 mK

thermal coupling

thermometer
(NTD Ge)

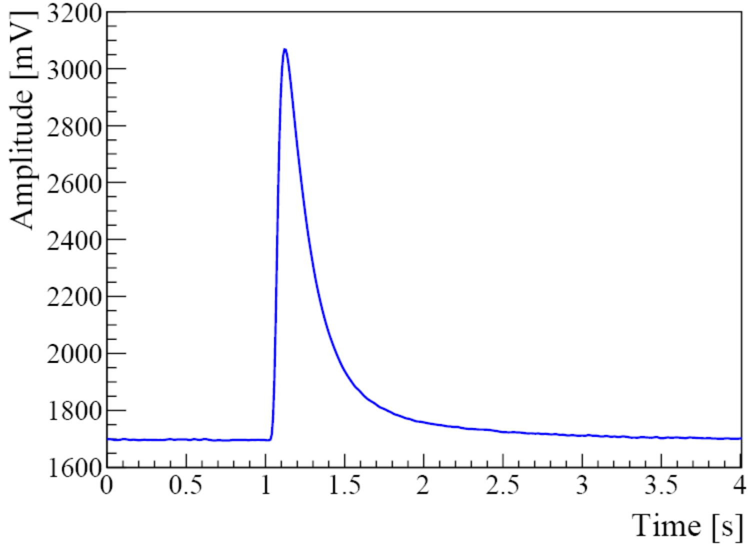
absorber

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

$$\tau = \frac{C}{G}$$

C = heat capacity
G = thermal conductance

Model based on the assumption that the energy release in the crystal can be considered **instantaneous** because bolometers are very slow detectors.



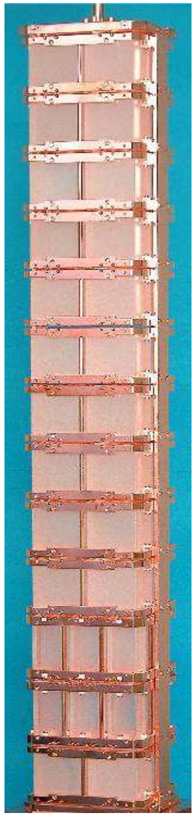
Pulse Shape parameters

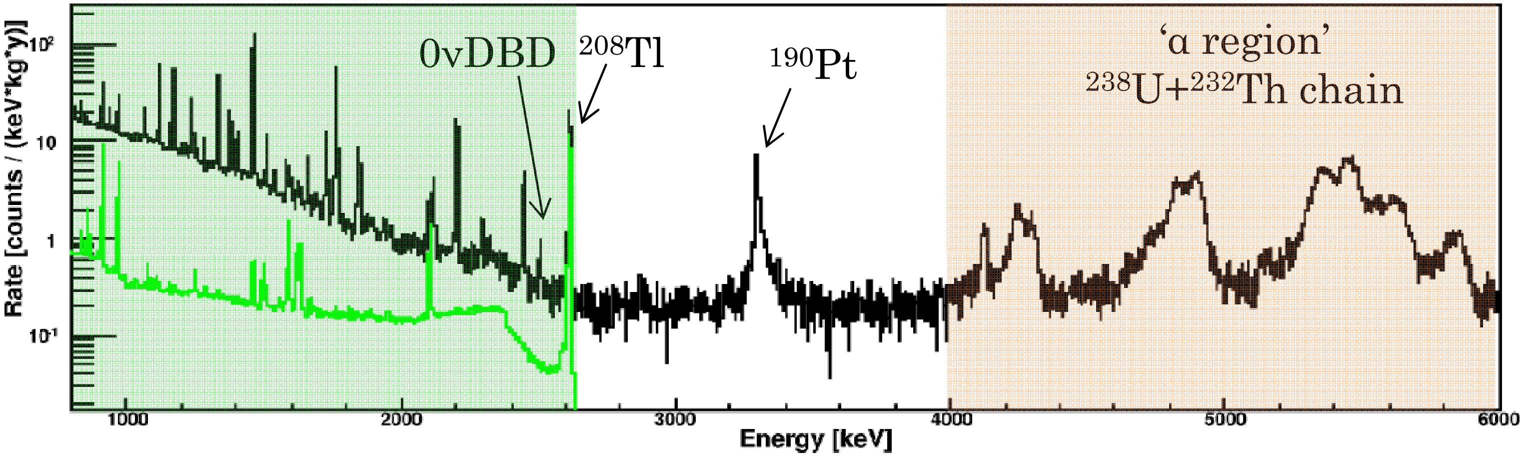
- **Amplitude**
- Rise Time ($t_{90\%}$-$t_{10\%}$)
- Decay Time ($t_{30\%}$-$t_{90\%}$)
- Test Value Right (TVR)
- ….

least square differences of optimally filtered pulse with respect to the filtered response function

Cuoricino & Surface contaminations

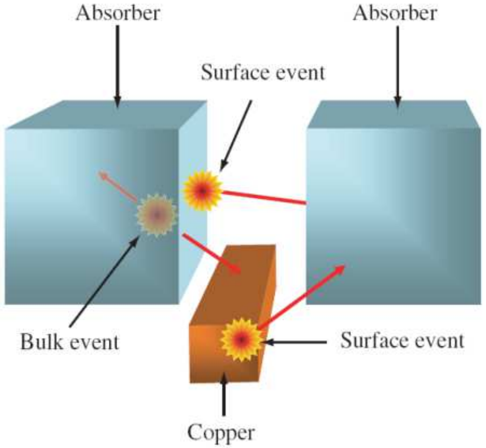
Cuoricino (2003 – 2008, 40.7 kg of TeO_2): the highest sensitivity experiment for 0vDBD of ^{130}Te ($Q_{\beta\beta}$ = 2528 keV, i.a.=33.8 %) based on the bolometric technique.





Cuoricino counting rate in the region of interest (**0.169±0.006 counts/keV/kg/y**):

- (10±5)% = **surface contaminations** of the TeO_2 crystals
- (30±10)% = multi-Compton events of the 2615 keV gamma from ^{208}Tl
- (50±20)% = **surface contaminations** of inert materials surrounding the crystals



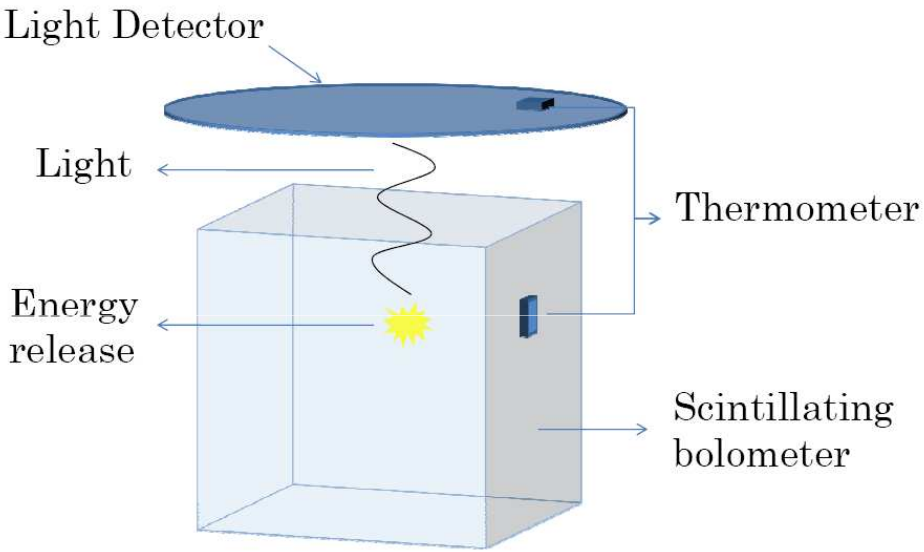
All the **passive** methods (crystal and copper surface cleaning, polyethylene, …) used to eliminate surface contaminations allowed to reach background of the order of ~$5\cdot10^{-2}$ counts/keV/kg/y.

To further reduce background a possible solution is an **active** method to identify the interacting particles:

scintillating bolometers.

Scintillating Bolometers

Double read-out: informations about the nature of the interacting particle.



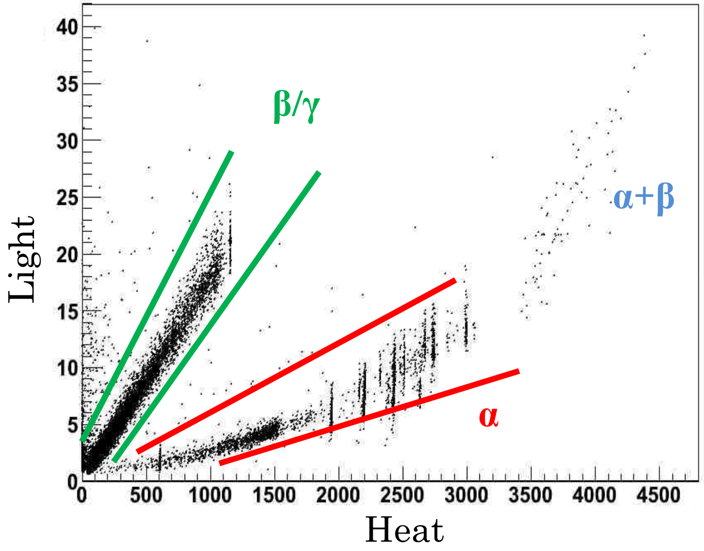
Light Detector

Light

Thermometer

Energy release

Scintillating bolometer



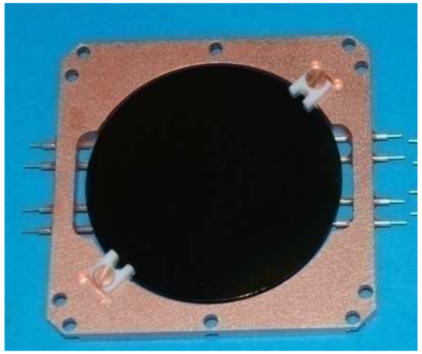
The light yield depends on the type of the interacting particle.

The Light Detector & the reflecting foil

- Small detector (=small heat capacity) for small amount of energy (scintillation light)

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

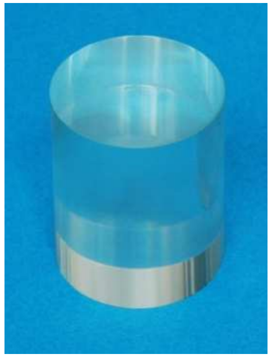
- 'Dark' detector to absorb all the scintillation light
- Reflecting foil around the scintillating crystal to collect all the scintillation light



Ge slab
(Ø~50 mm, h~0.5 mm)

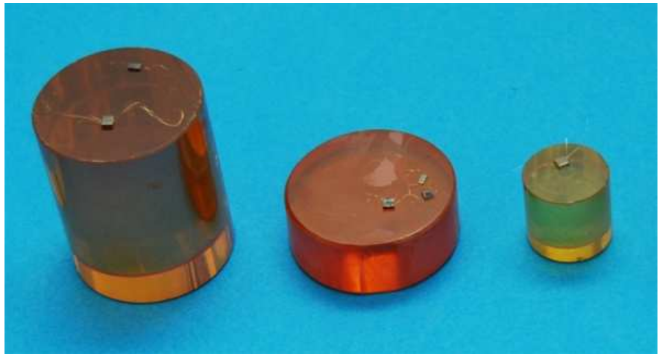
The optimum scintillating bolometer for 0vDBD

In these years a lot of scintillating crystals differing in compound, dimensions, shape, … tested to search the optimum scintillating bolometer for 0vDBD:

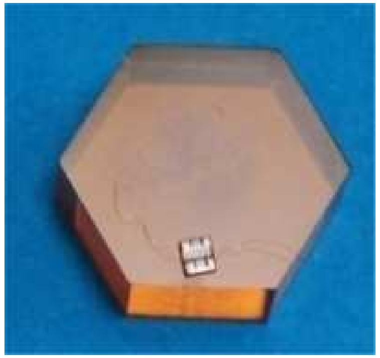


$CdWO_4$

$CaMoO_4$



ZnSe



$ZnMoO_4$

Some features taken into account for the scintillating bolometer selection:

- 0vDBD isotope with high Q value (low background region, favorable space factor, …)
- ‘High’ isotopic abundance (or enrichment possibility)

- Low radioactive contaminations
- Big crystals

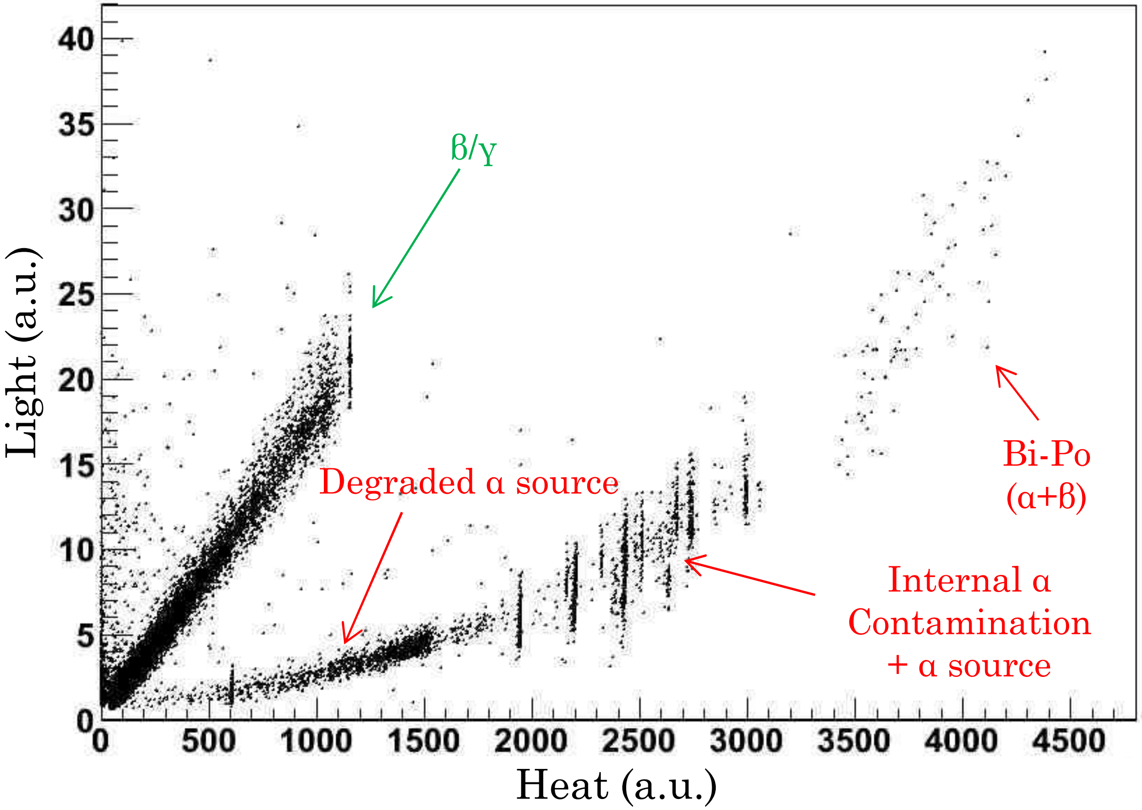
- Good thermal response (i.e. **high energy resolution**)
- **High discrimination power**

Scintillating Bolometers - $CaMoO_4$

Ø=35mm
h=40mm
158 g

$Q_{\beta\beta}(^{100}Mo)$ = 3030 keV
i.a. = 9.6 %

$Q_{\beta\beta}(^{48}Ca)$ = 4270 keV
i.a. = 0.187 %



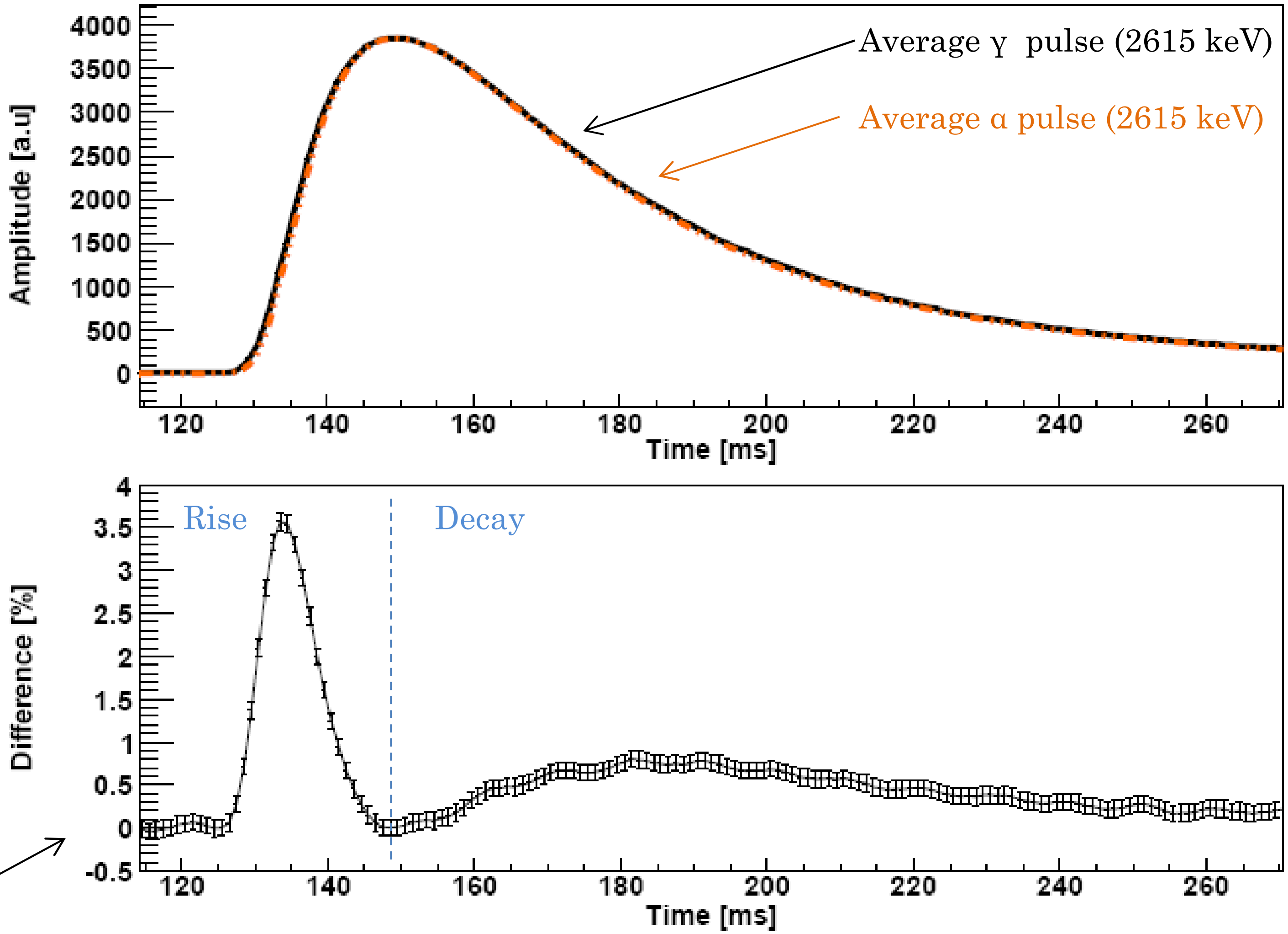
FWHM (2615 keV) = 9 keV

Quenching Factor = 0.174

ratio of the scintillating yield of an interacting particle (α, neutron, nucleus) with respect to the LY of a ß/γ event at the same energy

Scintillating Bolometers - $CaMoO_4$

For the first time differences between α and β/γ pulse shape in the main bolometer were observed.



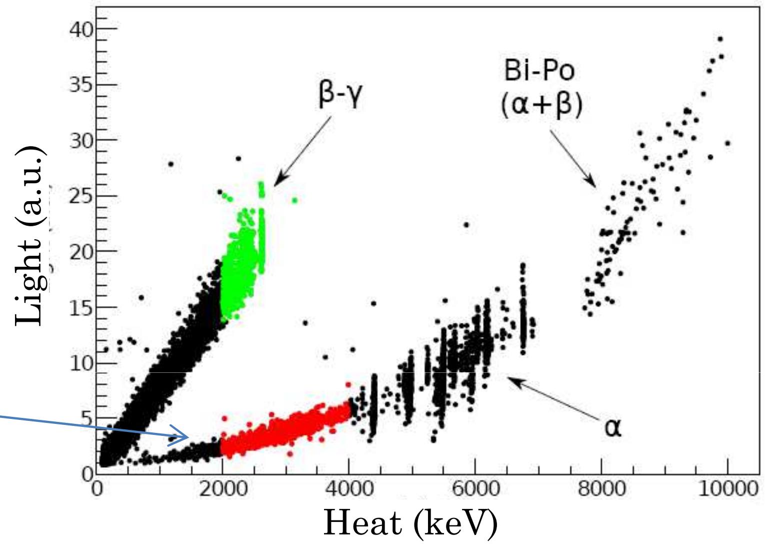
Average γ pulse (2615 keV)

Average α pulse (2615 keV)

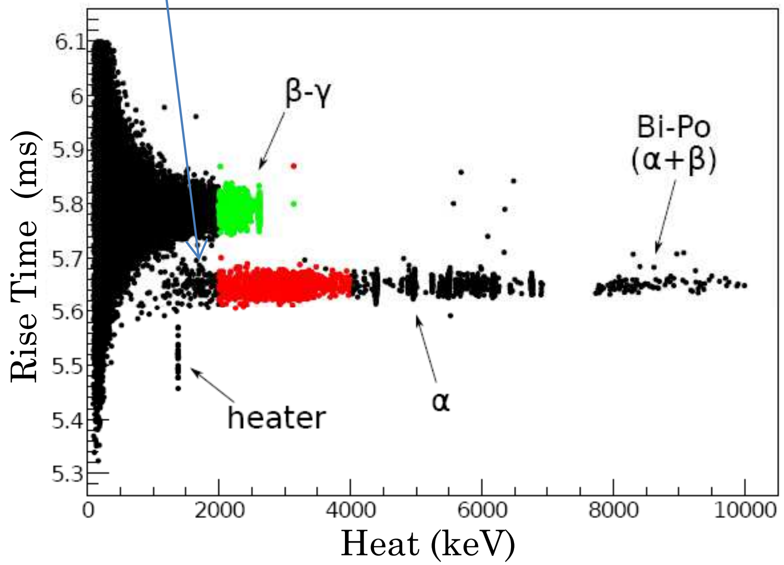
Percentage difference between average α and γ pulses.

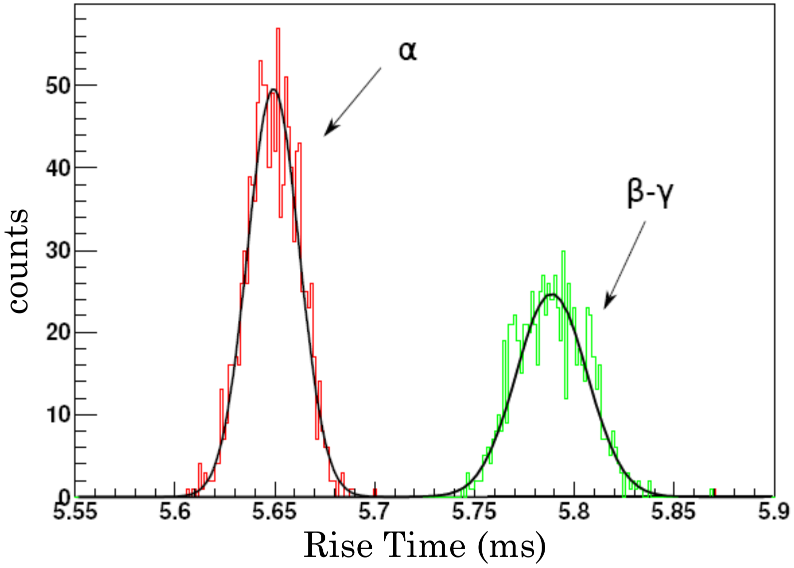
NIM A 617 (2010) 478
Astroparticle Physics 34 (2011) 797

Scintillating Bolometers - $CaMoO_4$



Degraded α source in order to have many α events in the 2-4 MeV region.

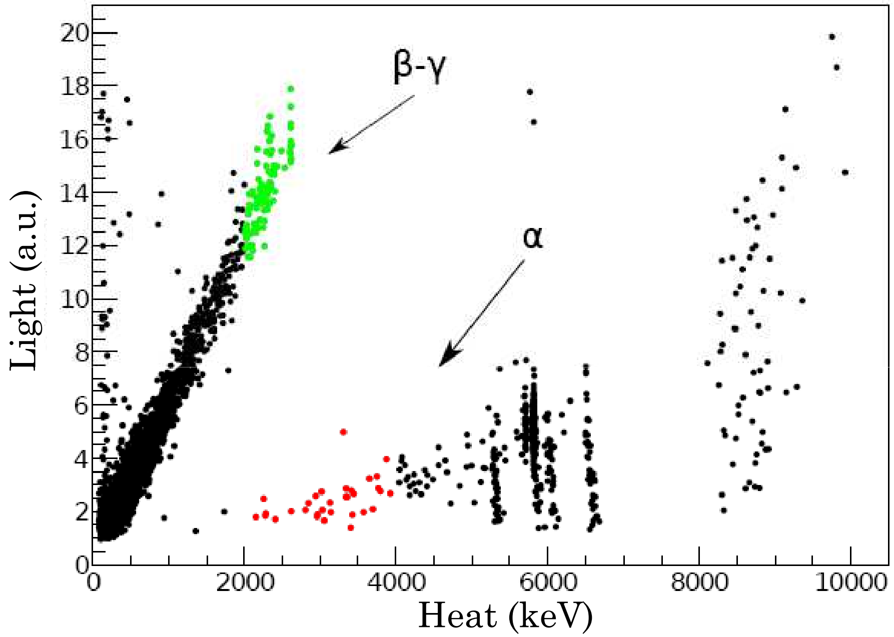


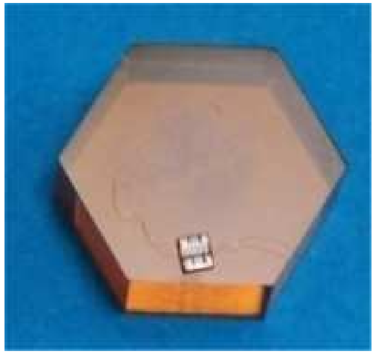


Rise Time discrimination power = 6.5

$$D_{RiseTime}(E) = \frac{RiseTime_{\beta/\gamma} - RiseTime_{\alpha}}{\sqrt{\sigma^2_{\beta/\gamma} + \sigma^2_{\alpha}}}$$

Scintillating Bolometers - $ZnMoO_4$



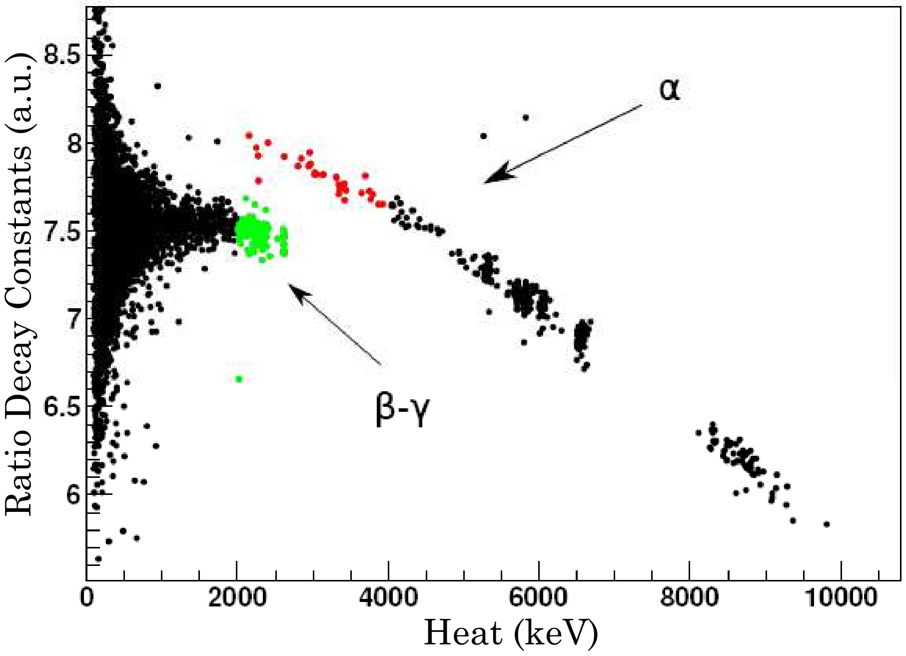


$Q_{\beta\beta}(^{100}Mo) = 3030$ keV
i.a. = 9.6 %

diagonal = 25mm
h = 11mm
19.8 g

$$\Delta V(t) = (e^{-t/\tau_1 + A_1} + e^{-t/\tau_2 + A_2})$$

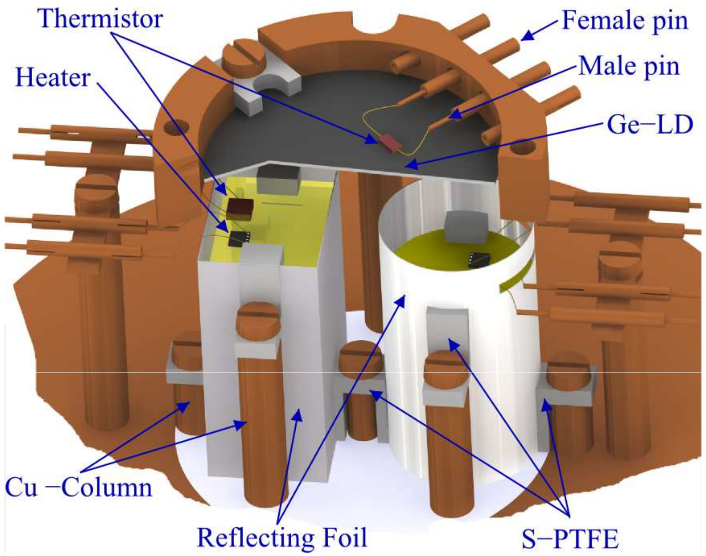
$$Ratio\ Decay\ Constants\ (RDC) = \frac{\tau_1}{\tau_2}$$

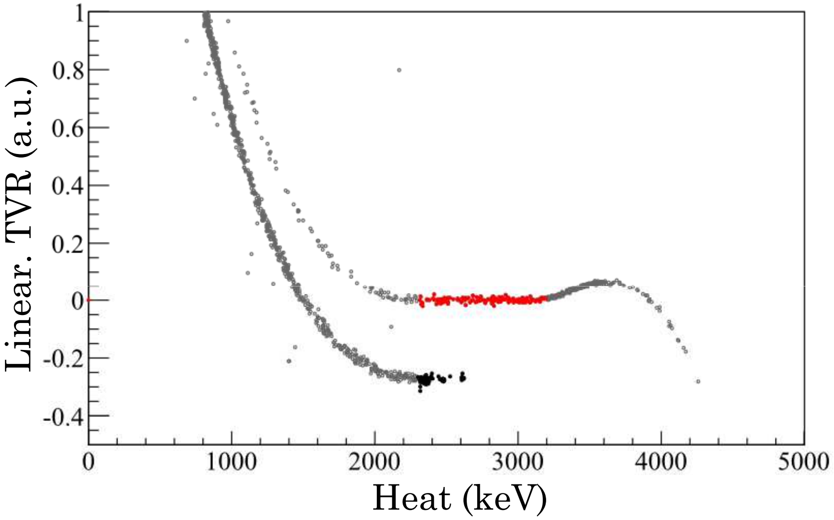


RDC discrimination power = 5.4

Journal of Instrumentation 5 (2010) P11007

Scintillating Bolometers - $ZnMoO_4$ (New crystals)



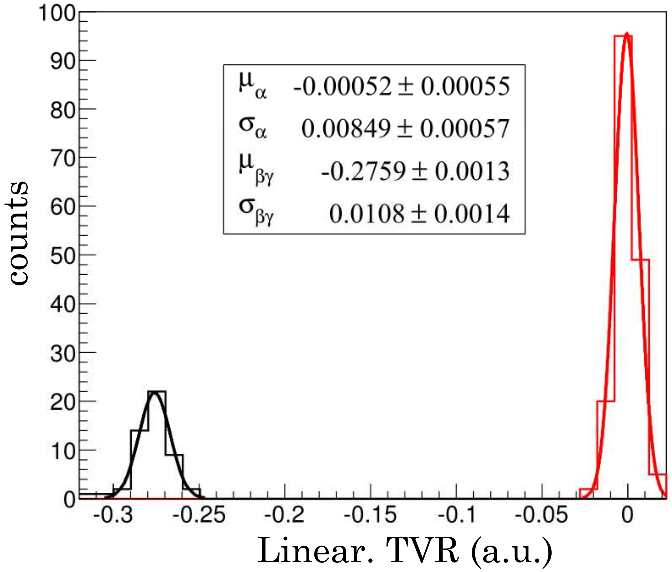


28.5x18.4x13.2 mm^3
29.9 g

Ø=18.5 mm
h=22.3 mm
27.5 g

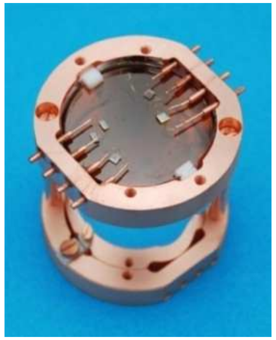
Shape variable	Discrimination Power
Rise Time	4.9
Decay Time	4.6
TVL	4.2
TVR	20.0

FWHM (2615 keV) = 3.8 keV



Astroparticle Physics 35 (2012) 813

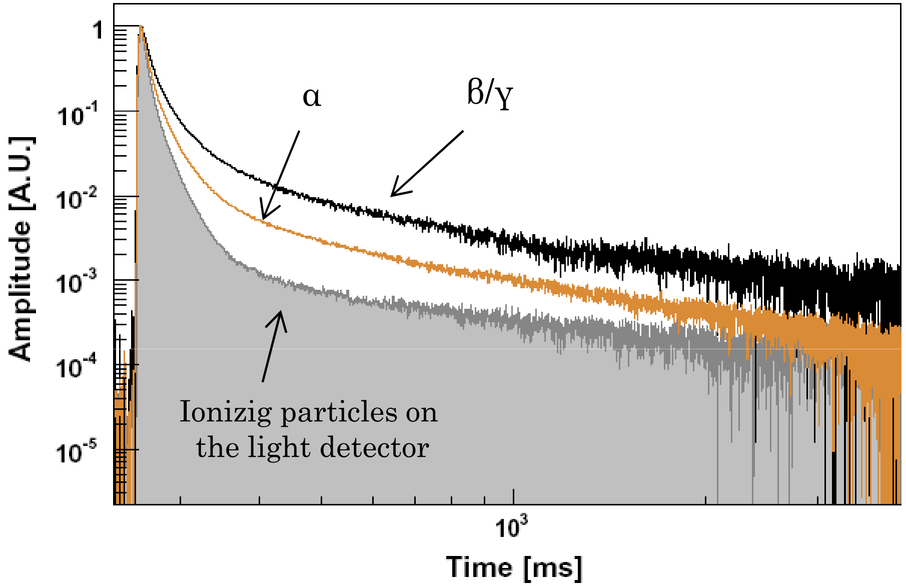
Scintillating Bolometers - ZnSe



Ø = 40 mm
h = 50 mm
337 g

$Q_{\beta\beta}(^{82}\text{Se}) = 2996$ keV
i.a. = 8.7 %

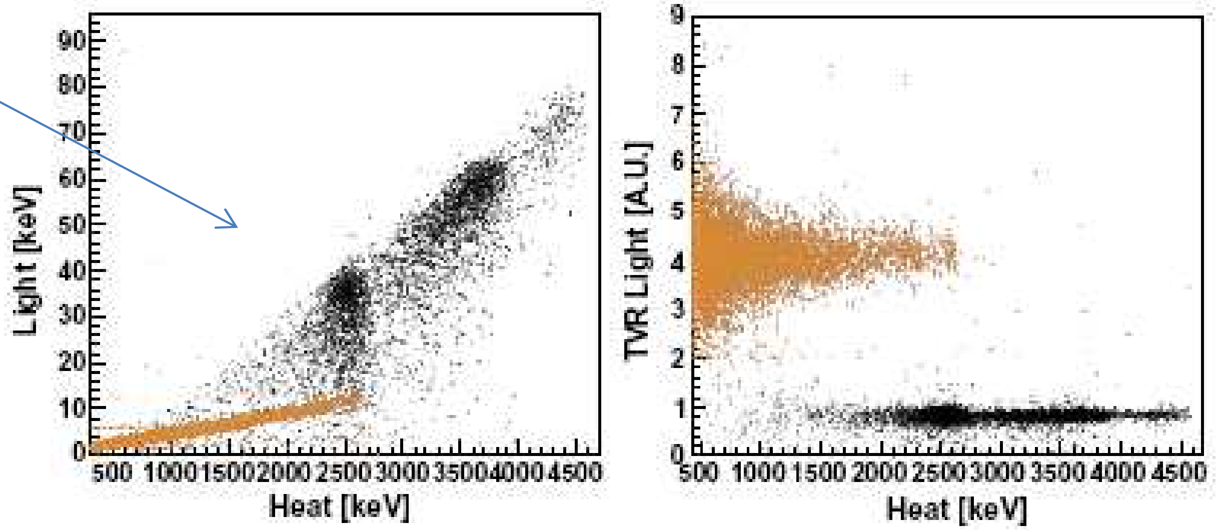
Averaged pulses on the light detector



Ionizig particles on the light detector

Different pulse shape between α and β particles in the **light** detector.

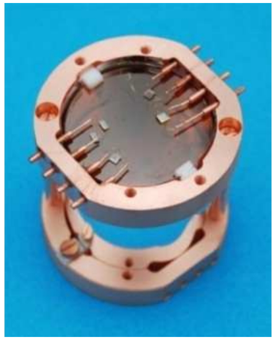
‘Inverse’ Quenching Factor in ZnSe



Light TVR discrimination power = 15

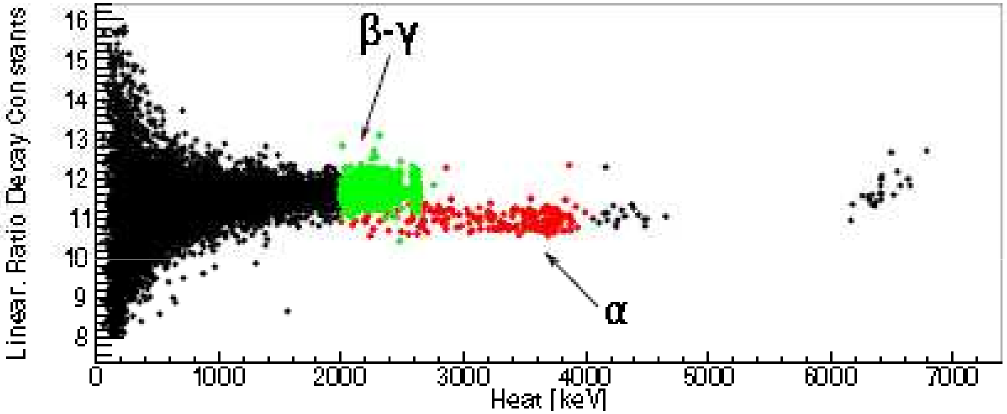
Astroparticle Physics 34 (2011) 344

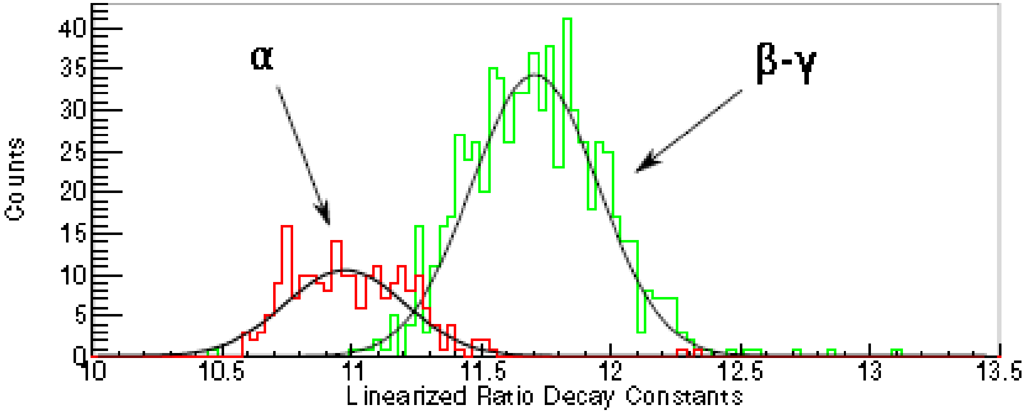
Scintillating Bolometers - ZnSe



Ø = 40 mm
h = 50 mm
337 g

$Q_{\beta\beta}(^{82}Se) = 2996$ keV
i.a. = 8.7 %





Also on the scintillating crystals itself a smaller discrimination was observed.

RDC discrimination power = 2.2

The effect that produce different pulse shape must be convolved with the bolometric response that are very different between scintillating crystals and light detectors.

Scintillating Bolometers & Background

In scintillating bolometers, thanks to the pulse shape analysis is already possible to completelly remove alpha background in the MeV energy region.

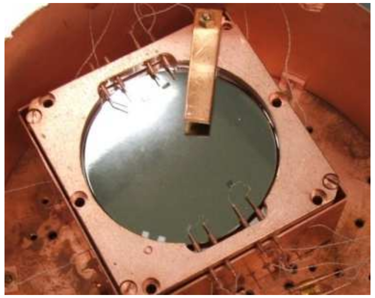
Crystal	**Discrimination parameter**	**Light Detector**	**Discrimination Power in the MeV region**
$CaMoO_4$	Rise Time	No	6.5
$ZnMoO_4$	Ratio Decay Const	No	5.4
$ZnMoO_4$ (new crystal)	TVR	No	20
ZnSe	TVR Light	Yes	15
ZnSe	Ratio Decay Const	No	2.2

Very interesting for **Dark Matter** searches

In the low energy region (lower than hundreds keV) the discrimination power based on pulse shape analysis hasn't already proven to be enough.

However a lot of work can be still done (more performing thermistors, dedicated electronic and data acquisition, ...)

Scintillating Bolometers - Pulse Shape Analysis



Pulse Shape Analysis

NO LIGHT DETECTOR

NO REFLECTING FOIL

Pulse Shape Analysis vs Light Yield

- Easier installation

- Lower number of acquisition channels
    - reduction of costs and work
    - reduction of thermal link between room temperature and working temperature of few mK.

- Discharge of the light detector
    - significant reduction of costs (light detector, thermistors, electronics)
    - a remarkable R&D work must still be done in order to optimize the light detectors that, in this case, could be avoided.

- Discharge of the reflecting foil
    - considerable simplification of the structure
    - possibility of anti-coincidence between crystals in order to reduce furthermore the α background

Scintillating Bolometers - Pulse Shape

Assumption: the processes that lead to the thermal pulse formation (i.e. the production of scintillation light and of phonons and their collection in the sensor) **can not be considered instantaneous** even in slow detectors such as the bolometers.

If the energy release is instantaneous, there are no ways to explain what has been observed!!

It 's also important to consider that the thermal signal measured is given by the convolution of the release of energy with the bolometric response .

- detector response (heat capacity, thermal coupling to the heat sink, working temperature, …)
- electronic (antialiasing Bessel filter, wires parasitic capacitance, ...)
- acquisition (sampling rate).

Time for the energy release (τ_E) vs bolometric response:

- $\tau_E <<$ rise time → could not be observed because filtered (antialiasing Bessel filter, wires capacitance)
- $\tau_E \leq$ rise time → observed mainly on parameter connected to the **rise time**
- $\tau_E \geq$ rise time → observed mainly on parameter connected to the **decay time**
- $\tau_E >>$ rise time → could modify significantly the amplitude (evaluated whit the optimum filter approach)

Scintillating Bolometers - Pulse Shape

Time evolution of the thermal signal in scintillating bolometers:

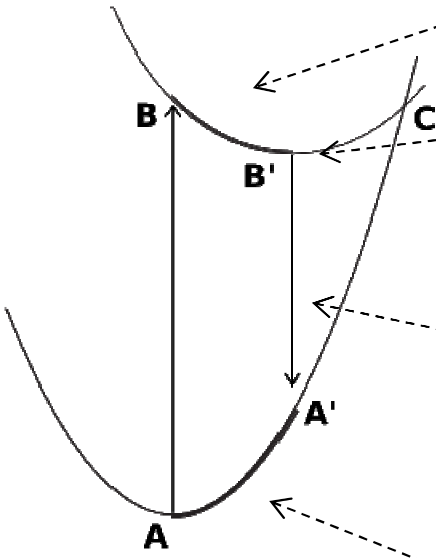
Particle interaction with the scintillating crystal

(1-ω) **(ω)**

Thermal processes

Thermal processes have a very fast time evolution ($<10^{-6}$ s). They can be considered instantaneous with respect to thermal pulse in macro-bolometer (rise time ~ 10^{-3} s)

Scintillation processes



‘prompt’ phonons

‘long-lived’ state

τ_{CaMoO4} (at 4K) = $3{,}8 \cdot 10^{-4}$ s

scintillation

(~50% of the energy flows in the scintillation channel in molybdates)

‘delayed’ phonons

The bolometric signal in the scintillating crystal is given by the sum of all the emitted phonons (both in the thermal channel and in the scintillation channel) and those produced by self-absorption of the scintillation light.

Scintillating Bolometers - Pulse Shape

The percentage of energy flowing in the scintillation channel depends on the type of the interacting particle: particles with a high ionization density (α) occupy all scintillation levels up to saturation.

The percentage that flows into the thermal channel as a result of the interaction of a α particle is greater than the β/γ ones.

$$\omega_{\alpha} < \omega_{\beta/\gamma}$$

This difference produce

Different L.Y. for α and β/γ

Different thermal pulse shape

The number of 'delayed' phonons is proportional to ω

To apply this model to the bolometric signal some work is still needed (convolution of the production of phonons with the response of the bolometer (link to the thermal bath), exponential behavior of the resistance, Bessel filter, ...).

Checks of the model are possible thanks to the different information available (2 pulses in the scintillating crystal + 2 pulses in the light detector).

Journal of Low Temperature Physics 167 (2012) 504

Conclusions

- The bolometric technique is particularly suited to rare events studies (high resolution, low background, …) but surface contamination.

- Development of **active** rejection methods (**scintillating bolometers**). Some of the tested crystals have shown very high discrimination power for 0vDBD.

- Interesting discovery: the **Pulse Shape Discrimination**
    - Observed on different scintillating crystals
    - Much more enough to completely remove α background in 0vDBD.
    - Not yet enough for low energy studies (e.g. Dark Matter) but considerable room for improvement

- For a huge multi-detector array of bolometer, the pulse shape discrimination could greatly simplify the assembly and reduce costs respect to a double read out needed with scintillating bolometers.

- An explanation of the **Pulse Shape Discrimination** based on the energy partition in the heat and scintillation channels is presented.

Thank you