Aboveground test of an advanced Li_2MoO_4 scintillating bolometer

Michele Mancuso

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Outline

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- Measurements and results
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  - Li_2MoO_4 scintillating bolometer
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Li_2MoO_4 properties and characteristic

- Molibdate compound free from natural long living radioactive isotopes
- Scintillating crystal
- High concentration of Mo (55% in mass)
- Easy to grow
- It can be sensitive to DM nuclear recoils because of the low mass of Li
- It's a good neutron detector due to the high cross section to neutrons capture of ^{6}Li
- Interesting for the searches for quasi-monoenergetic solar axions coupled to nucleons through resonant excitation of Li nuclei

Property	Value
Density (g/cm^3)	3.02 – 3.07
Melting point (K)	974 ± 2
Hygroscopicity	Weak
Index of refraction	1.44

Property	Value
Wavelength of maximum emission (nm)	540 at 85 K 590 at 8 K 600 at 85 K
Radioactive contamination (mBq/kg)	
^{40}K	170(80)
^{232}Th	≤ 0.11
^{238}U	≤ 0.09

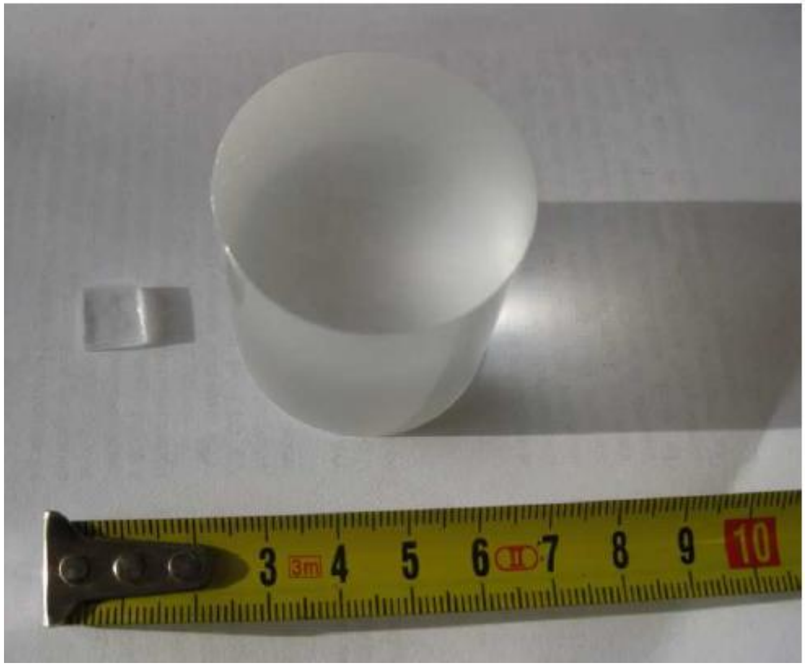
Li_2MoO_4 samples

Optically clear defect-free Li_2MoO_4 crystals 25−55 mm in diameter and 70 − 100 mm in length with mass of 0.1 − 0.37 kg were grown.
Two elements were cut from one of the boules:

- Luminescence measurements (10×10×2 mm) and
- Bolometric test (∅40 × 40 mm).

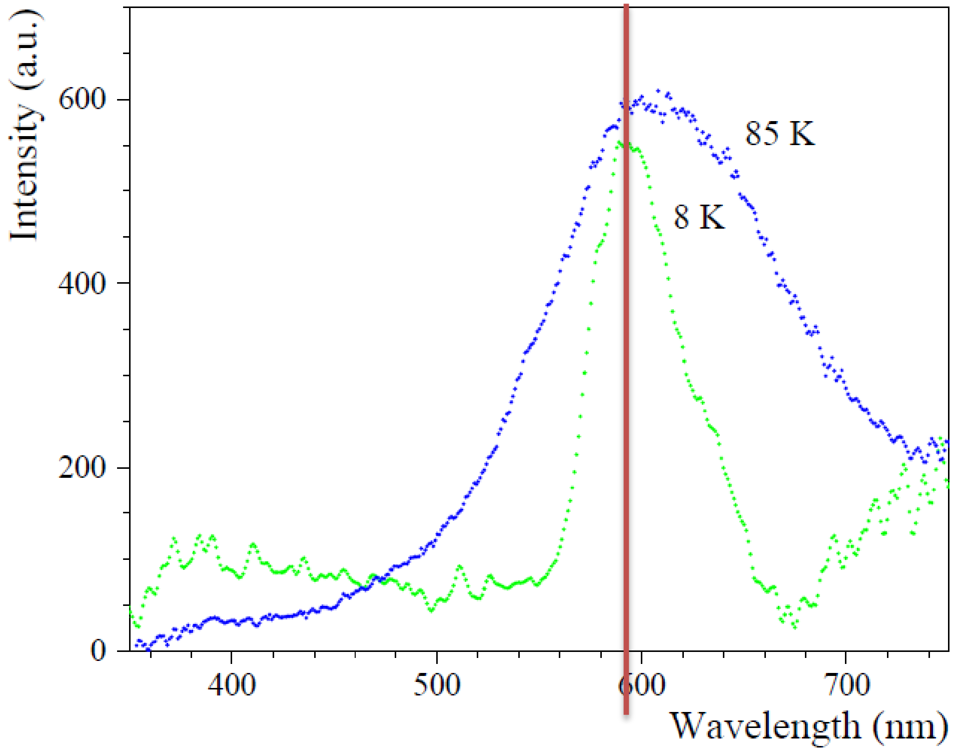
➢Most of the gathered experience on $ZnMoO_4$ can be extended

Test large Li_2MoO_4 crystal



Luminescence measurement

The luminescence of the $ZnMoO_4$ crystal sample (10×10×2 mm^3) was investigated under X-ray excitation.

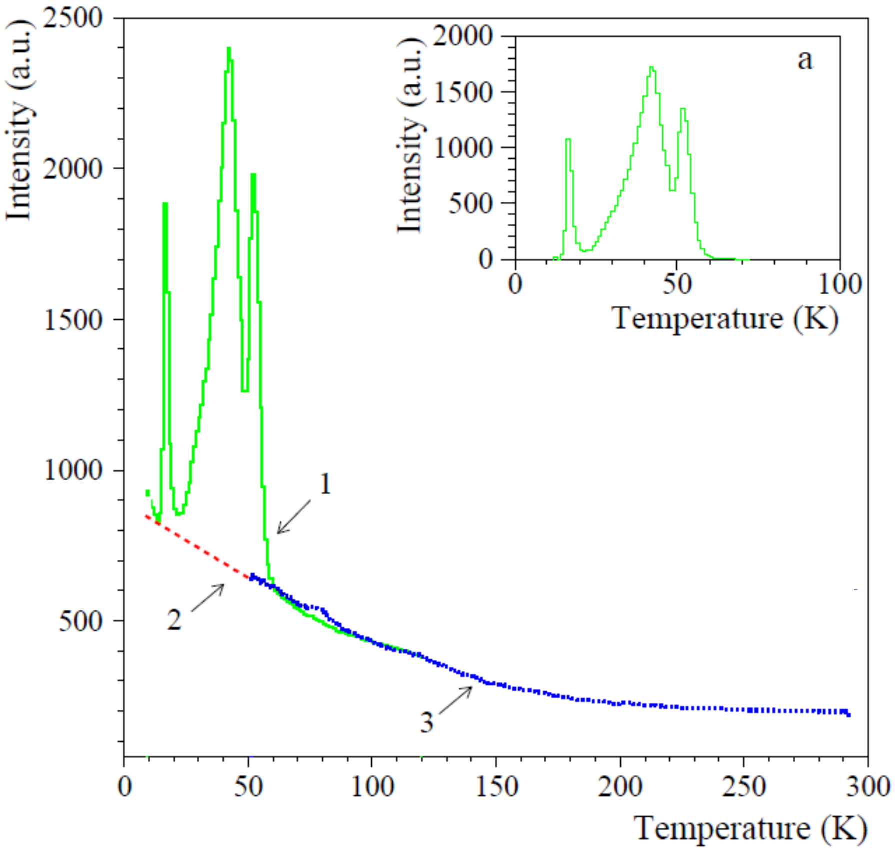


- The sample was irradiated by X-rays from a tube with a rhenium anode (20 kV, 20 mA).
- Light from the crystal was detected with two photomultiplier FEU-106 (350 – 820 nm) and FEU-83 (600 −1200 nm).
- The measurements were carried out using a high transmission monochromator MDR-2(diffraction grating 600 mm−1).

❖ The most intensive emission band was observed in the spectra with maximum at ≈ 600 nm at both temperatures

Luminescence measurement

The dependence of Li_2MoO_4 luminescence intensity in function of temperature was studied in the temperature interval 8−290K.



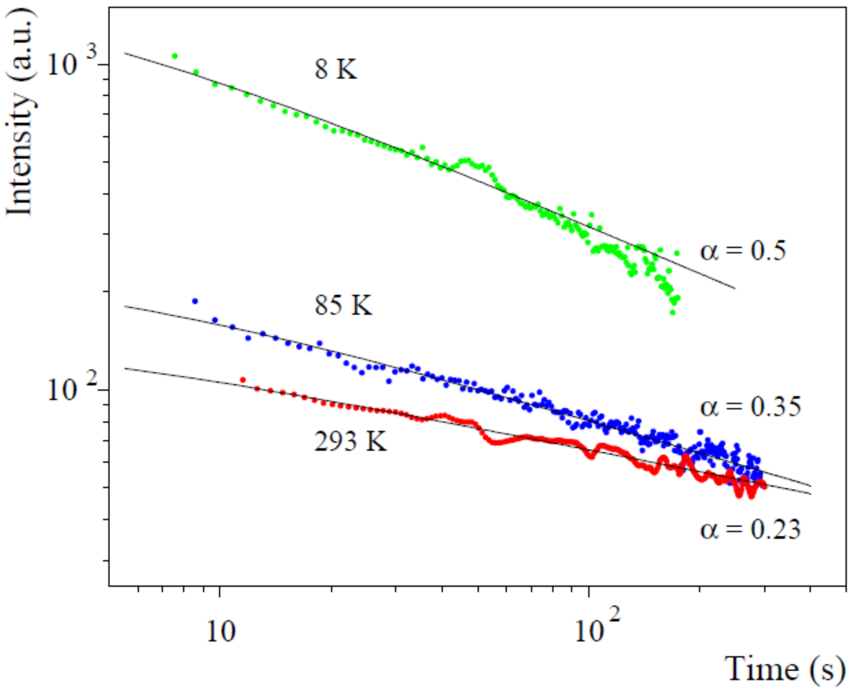
We have subtracted the thermo-stimulated luminescence (TLS) contribution assuming a linear dependence of the luminescence on temperature.

❖ The luminescence increases lowering the temperature.
(this behavior is exhibited by several Molibdates)

Luminescence measurement

The long-term phosphorescence was measured at 293 K, at 8 K and 85 K.
The phosphorescence decay curves can be approximated by the hyperbolic function:

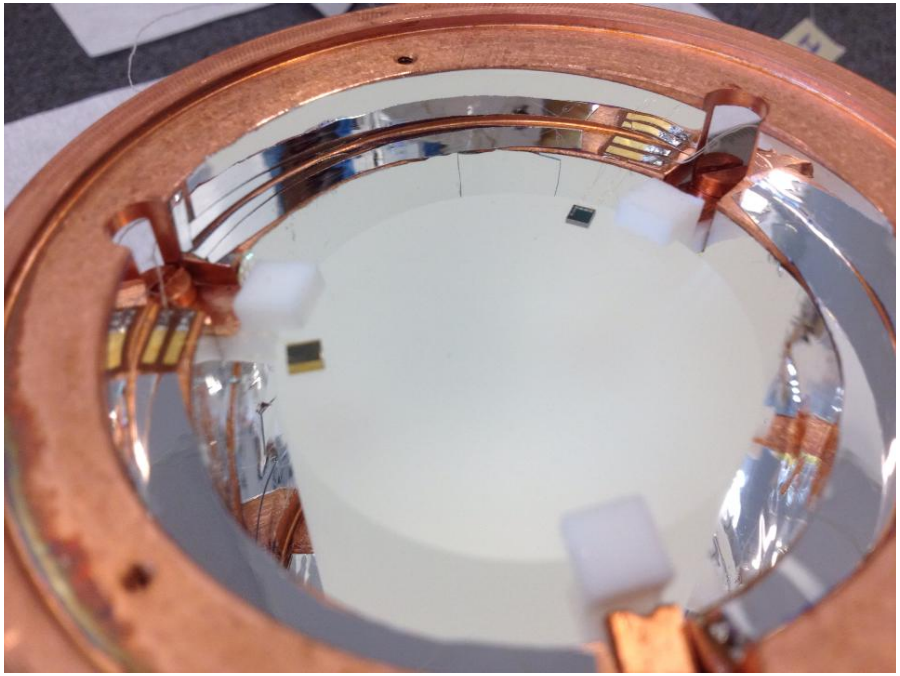
$$I = \frac{I_0}{(1 + a \times t)^{\alpha}}$$



I : intensity of phosphorescence
I_0 : intensity of phosphorescence after irradiation
a : coefficient which depends of material
α : degree of the hyperbolic function

α(8 K) = 0.5
α(85 K) = 0.35
α(293K) = 0.23

Bolometer assembly



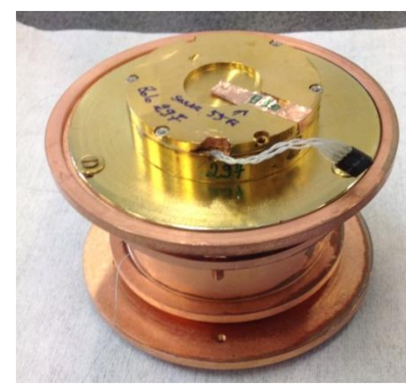
The cylindrical crystal with a size of ∅40 × 40 mm and a mass of approximately ~ 150 g, was used in a scintillating bolometer.

- Cylindrical copper holder
- Six PTFE elements fixing it at the copper support
- The Li_2MoO_4 was surrounded by a reflecting foil (VM2000, VM2002 by 3M) to improve light collection.
- Ge thermistor for the read-out of the heat signals.
- A heating element for temperature stability corrections

❖ The compound Li_2MoO_4 is slightly hygroscopic: The crystal (before assembly) and the detector (after assembly) were just kept under inert dry atmosphere and the installation time was minimized.

❖ We chose a light detector with an advanced design

N. Coron et al., Highly sensitive large-area bolometers for scintillation studies below 100 mK, Opt. Eng. 43 (2004) 1568.



Set-Up

❖ CSNSM Test facility (Orsay, France)

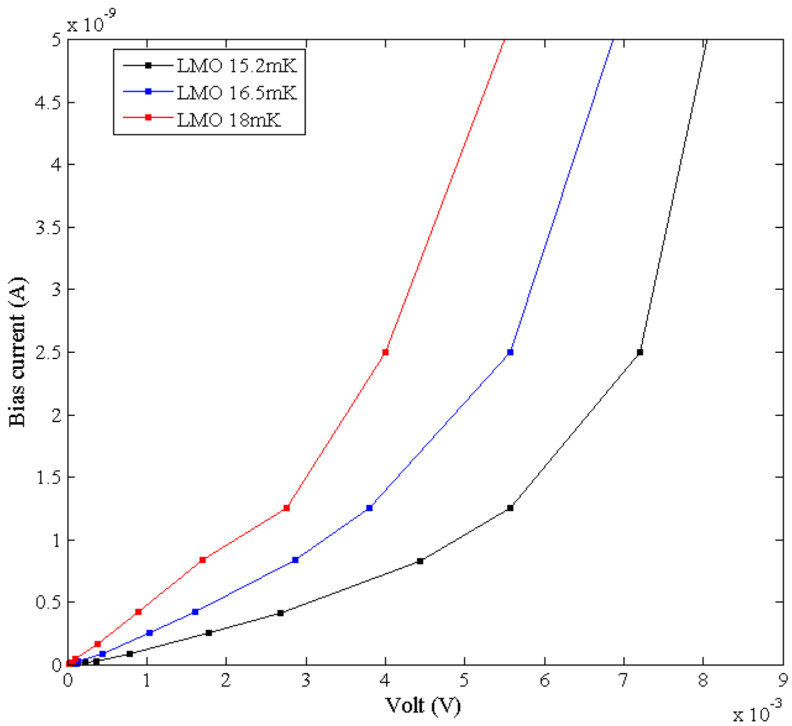
- Pulse tube cooler as a first cryogenic stage
- Free from cryogenic fluids
- Reach temperature below 12 mK
- The experimental space of 5 l allows measurement of three large mass bolometers
- Low electronic noise:
    - 30 nV/√Hz at 0.1 Hz
    - 7 nV/√Hz at 1 Hz
    - 3 nV/√Hz at f>3 Hz
- Mechanical decoupling at mixing chamber to reduce the effect of the pulse tube vibration.
- high purity lead shield (minimum thickness 10 cm) containing less than 30 Bq/kg of 210 Pb

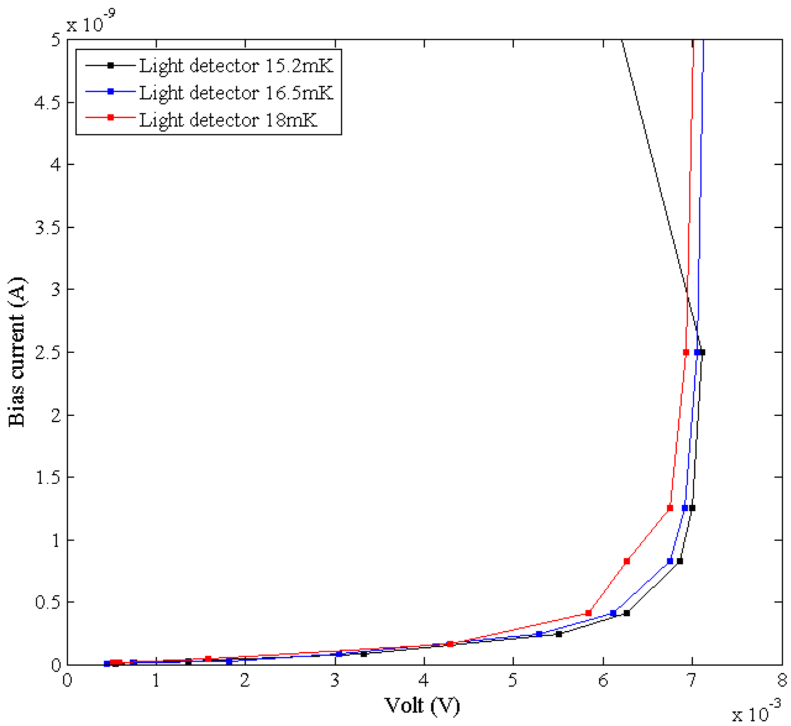
energy range keV	without lead counts/sec	with lead counts/sec	Reduction factor
100-500	1.840	0.084	0.046
500-1000	0.309	0.0156	0.050
1000-1500	0.114	0.0064	0.056
1500-2000	0.027	0.0034	0.126
2000-2500	0.014	0.0021	0.15
2500-3000	0.005	0.0016	0.32

This value refers to 24g $ZnMoO_4$ bolometer

Working point and measurement

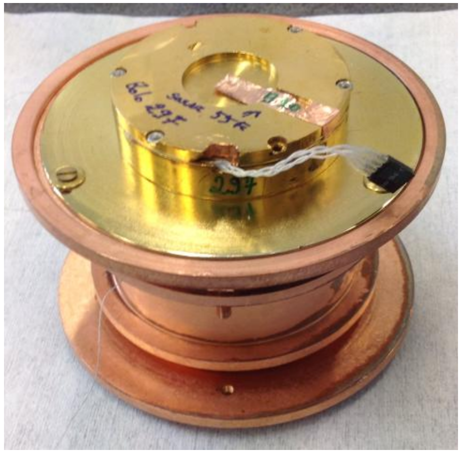
Detector	Temperature mK	Acquisition rate Hz	Applied bias nA	Load resistor GΩ	Applied gain	Bessel cut-freq Hz	NTD resistance MΩ
LMO	16.5	20000	5	1	1403	120	1.37
LD	16.5	20000	2.5	1	1403	675	2.82
LMO	15.2	20000	5	1	1403	120	1.61
LD	15.2	20000	5	1	1403	675	1.24



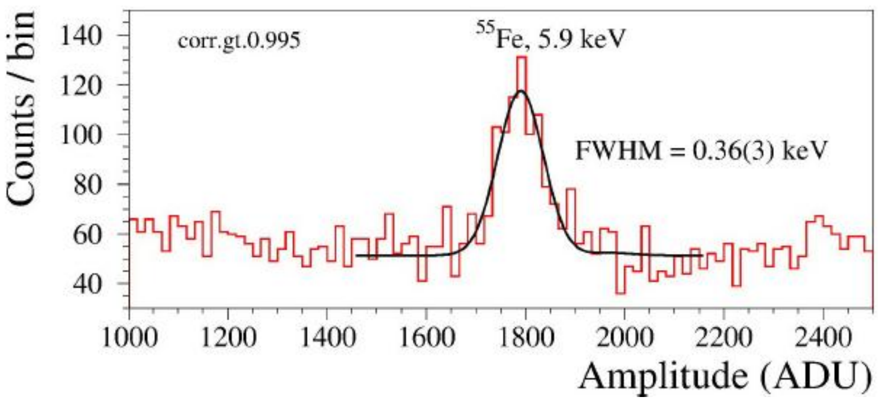


Light detector calibration

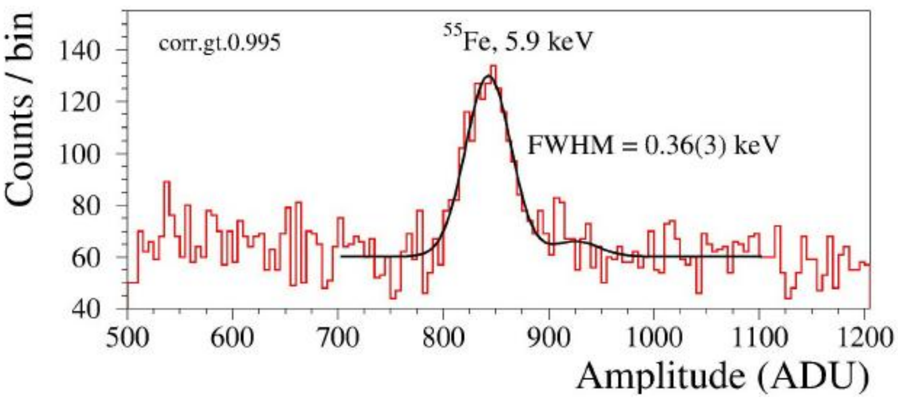
- The advanced light detector is a germanium wafer with ∅40 mm and thickness 45 μm.
- The Ge wafer suspension consists of 12 thin (∅6 μm) low-heat-conduction superconductive wires.
- On the rear side a small NTD Ge sensor (2×0.4×0.3mm) is glued.
- The thermal link is provided by a thin pure Ge slice.
- A low intensity 55Fe source facing the Ge wafer.
- The optical bolometer is adapted to the larger heat bolometer cavity with a silver coated copper diaphragm.



16.5 mK



15.2 mK

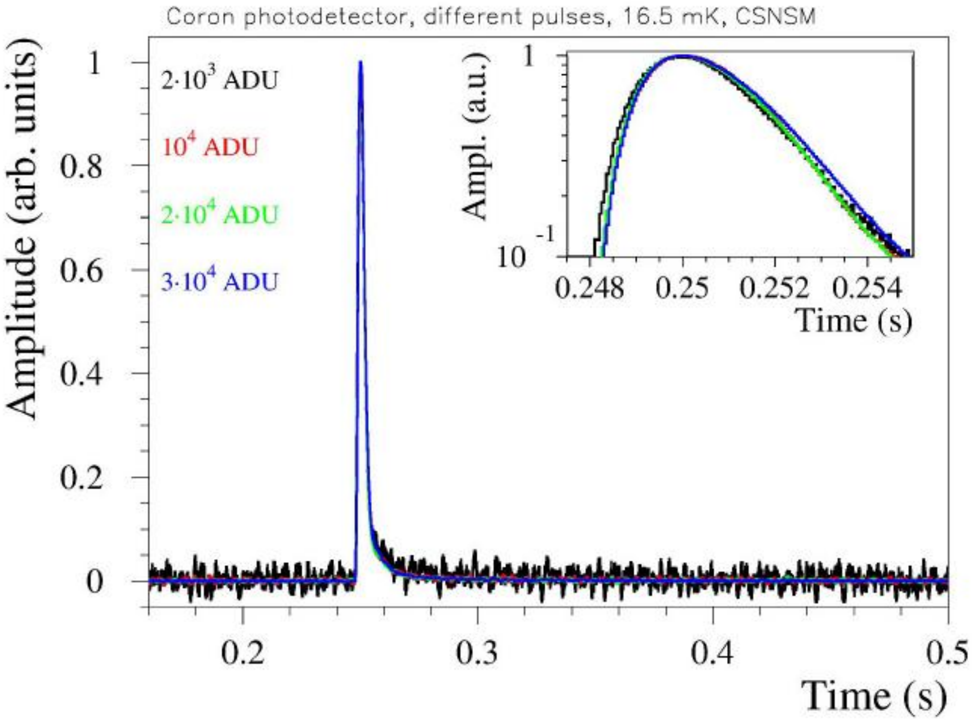


Sensitivity: 6.6 μV/Mev
FWHM Baseline: 0.073keV

Sensitivity: 2.559μV/Mev
FWHM Baseline: 0.082 keV

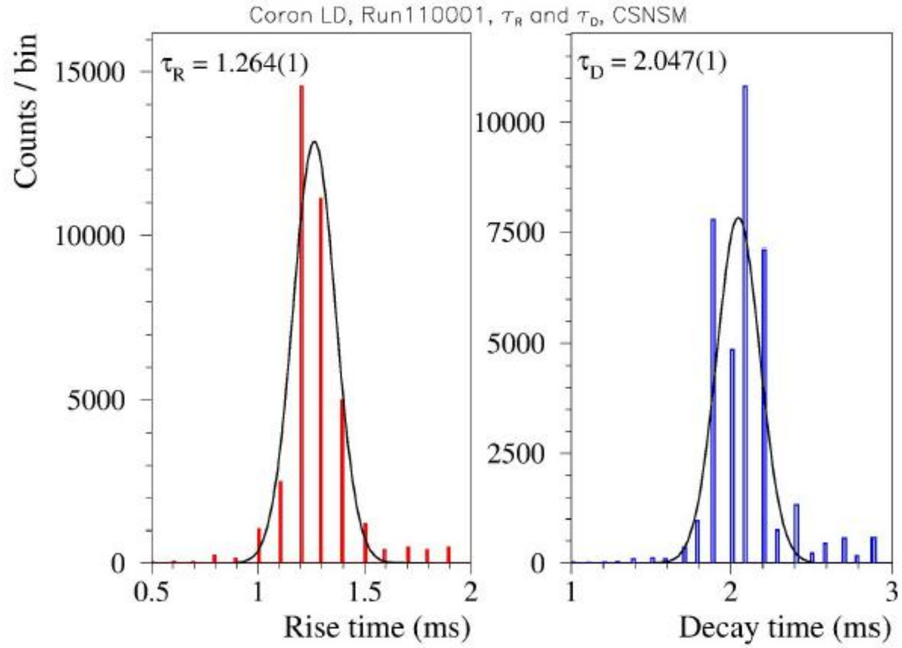
Light detector response

- Types of pulses depending from the energy



No energy dependence of pulse shape is observed.

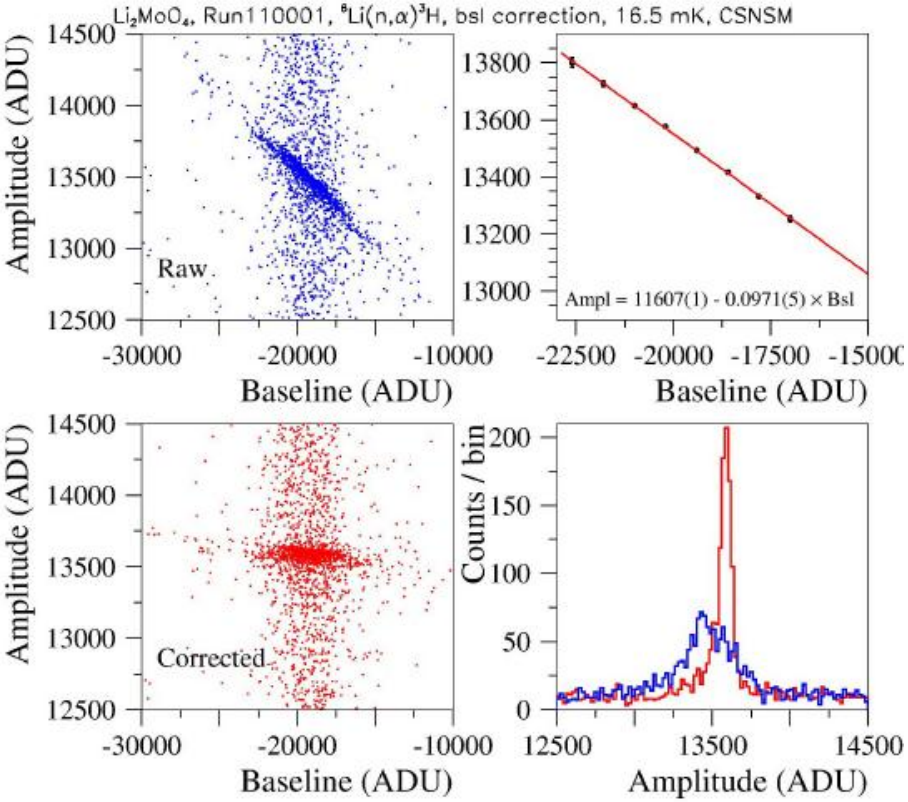
- Rise-time and decay-time analysis
  Energy region: 5.9 keV ^{55}Fe peak

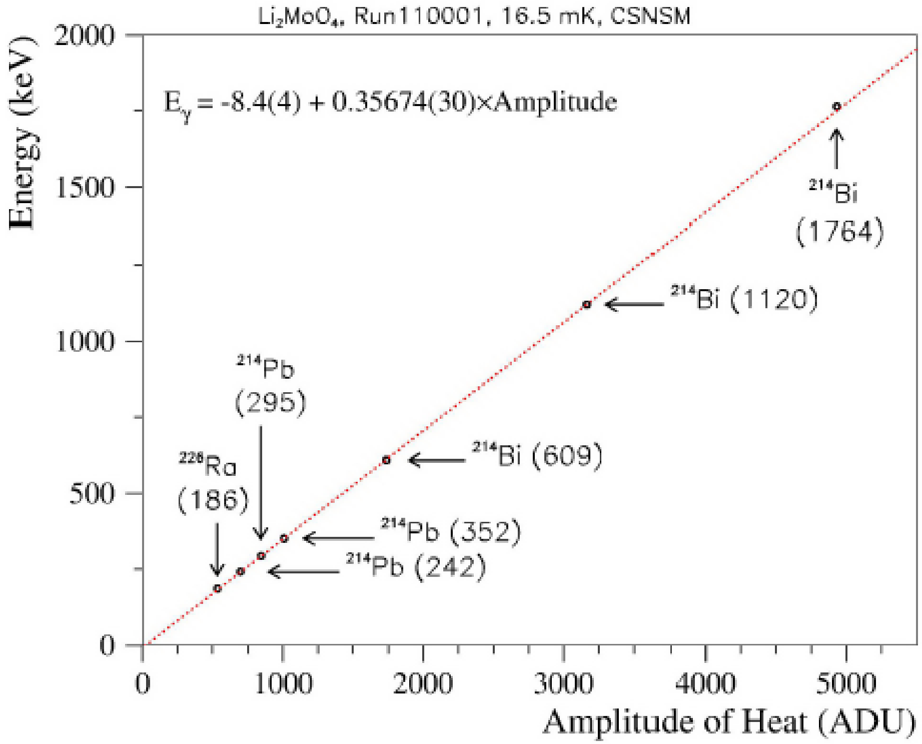


T	16.5mK	15.2mK
τ_{rise}	1.264 ms	0.914 ms
τ_{decay}	2.047 ms	1.342 ms

Li_2MoO_4 Calibration

➢The stabilization in temperature was achieved using the signals of neutron capture which provide a stable signal at 4.78 MeV

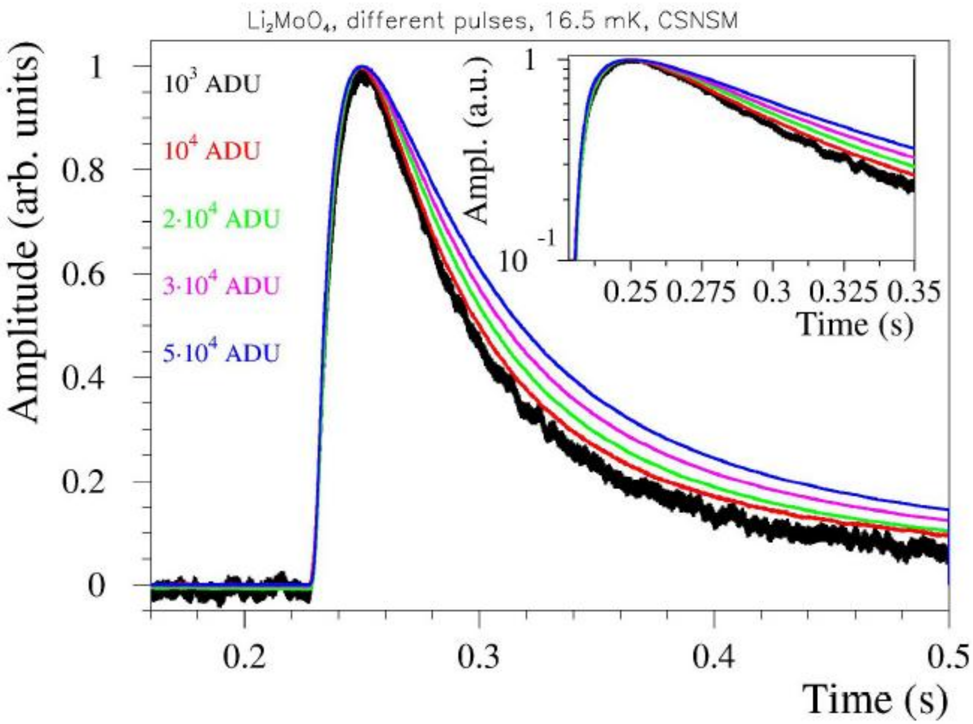




➢The calibration was made using the environmental radioactivity. The most dominant signals come from the Rn chain

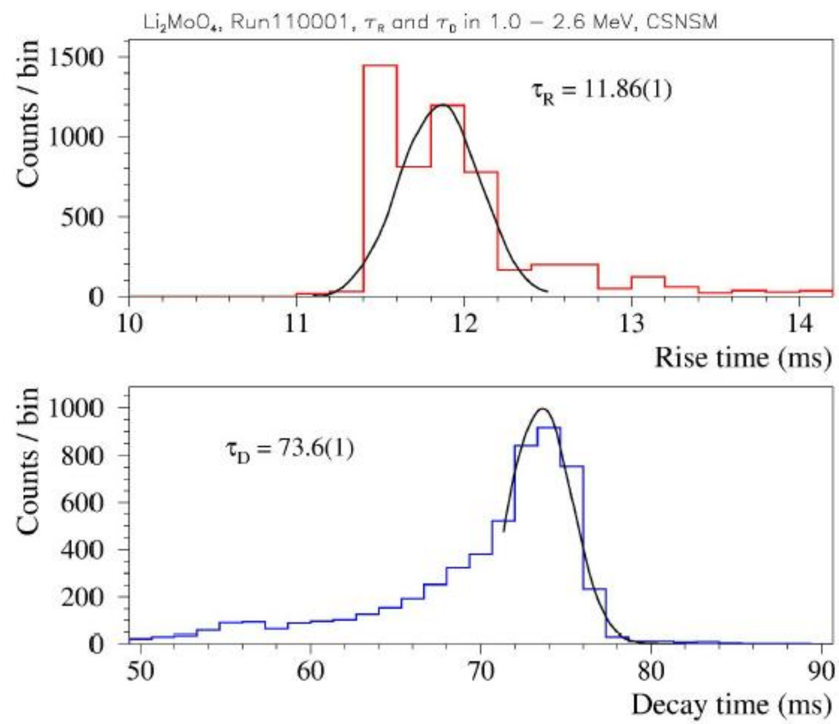
Li_2MoO_4 detector response

- ➢Types of pulses depending from the energy



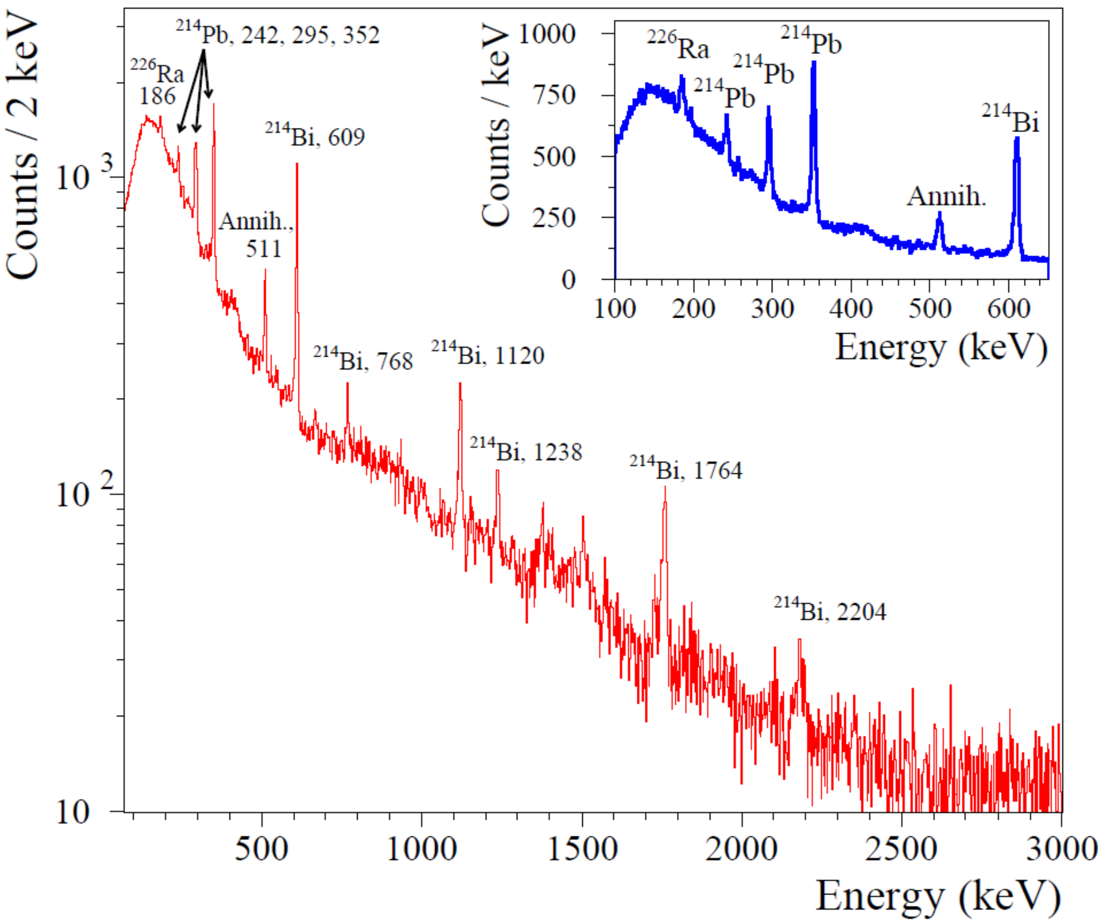
Energy dependence of pulse shape is observed.

- ➢Rise-time and decay-time analysis
  Energy region: 1-2.6 MeV



T	16.5mK	15.2mK
τ_{rise}	11.86 ms	10.04 ms
τ_{decay}	73.6 ms	75.0 ms

Li_2MoO_4 Total background



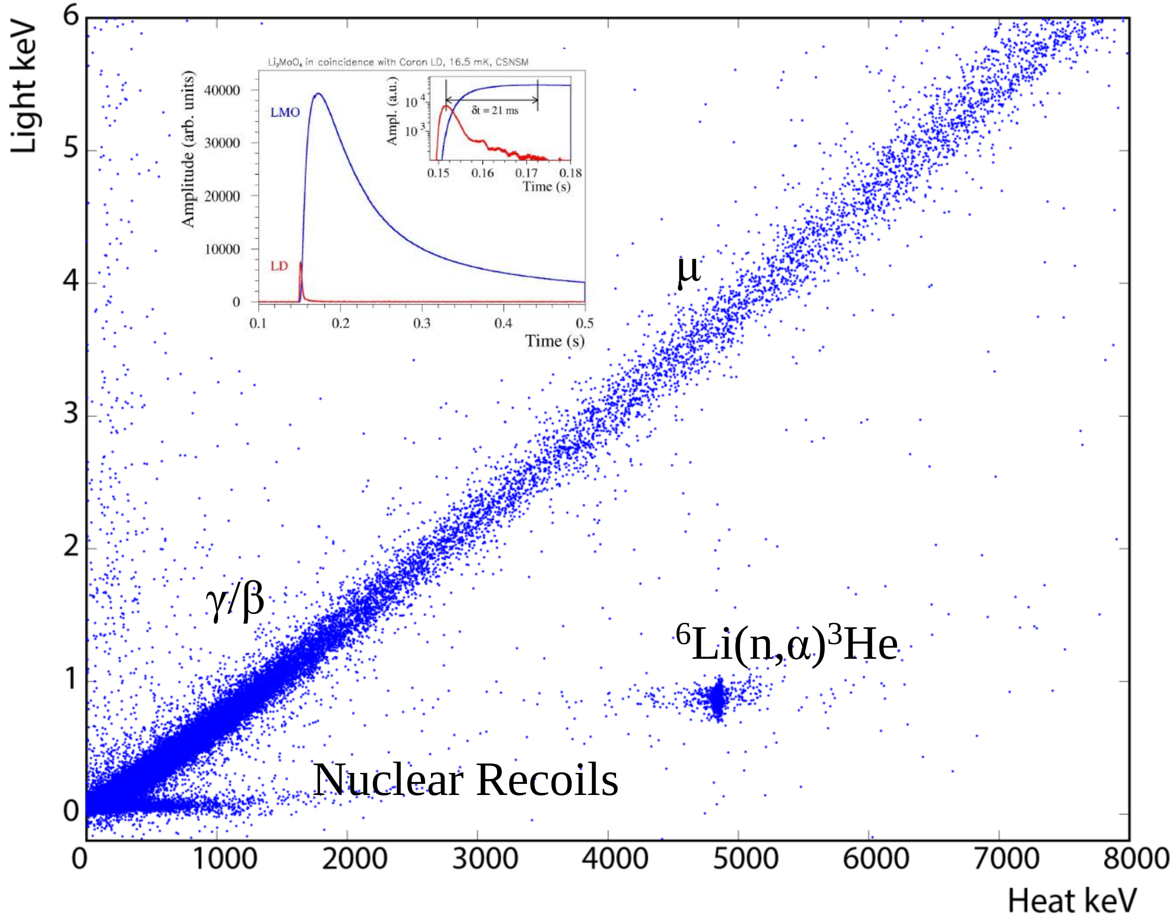
Energy spectrum measured in the Orsay aboveground set-up over 118 hours.

The observed lines belong to the ^{238}U radioactive chain and are all due to environmental radioactivity.

FWHM:
Baseline → 2.0 ± 0.1 keV

^{214}Pb @ 295 keV → 4.4 ± 0.4 keV
^{214}Pb @ 352 keV → 4.2 ± 0.2 keV
^{214}Bi @ 609 keV → 5.2 ± 0.3 keV

Scatter plot



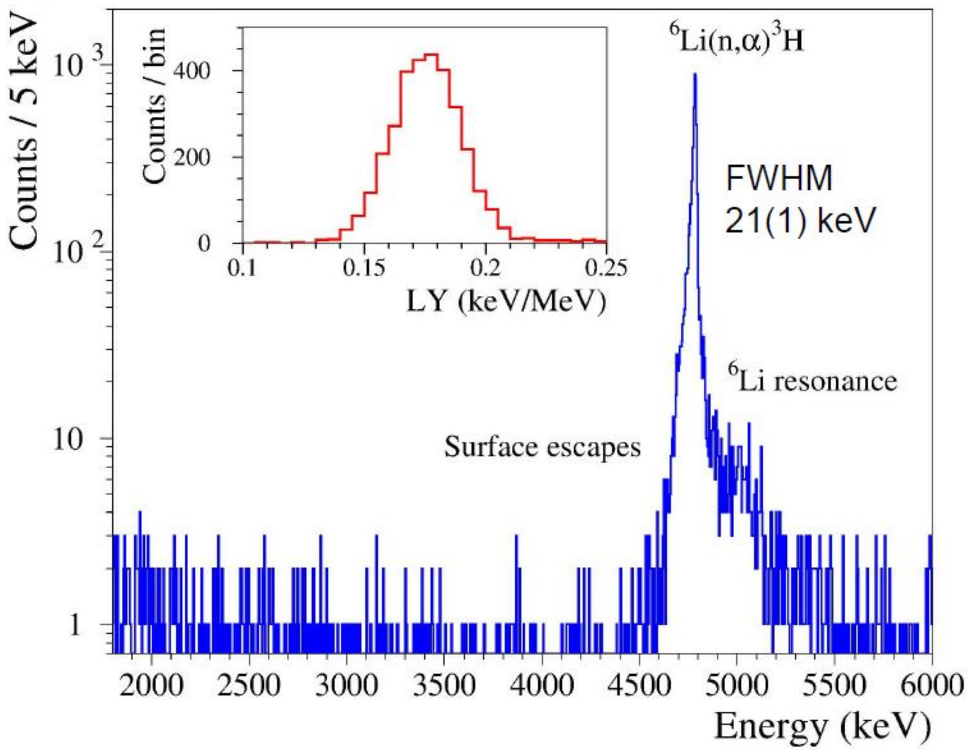
In the scatter plot, it is possible to recognize three main structures.

- A prominent fully populated band contains γ, β and cosmic muon events.
- A cluster of points with a much lower light emission with respect to the main band contains neutron absorption.
- A modestly populated band at low energies (extending up to ~ 2 MeV), without appreciable light emission contains nuclear recoils induced by fast neutrons.

$LY_{\gamma/\beta}$ = 0.7 keV/MeV @ 3MeV
$LY_{n\text{-capture}}$ = 0.17 keV/MeV

Neutron spectrum background

Energy spectrum of massive charged particles measured 118 hours requiring that the light yield be less than 0.25 keV/MeV. In fact, the isotope ^{6}Li, which has a natural abundance of 7.5%, has a very high cross section for thermal neutron capture (of the order of 940 barns).



The light yield at the α-triton peak (LY 0.17 keV/MeV) is significantly lower than that of fast electrons. The corresponding quenching factor of the mixed -triton events with respect to events is about 23% at ~ 4.8 MeV.

Conclusion and perspective

Conclusion

A low-temperature test of a scintillating bolometer based on a Li_2MoO_4 cylindrical crystal – with a size of ∅40 × 40 mm – was performed at ~ 15 mK in an aboveground pulse-tube cryostat housing a high-power dilution refrigerator in CSNSM (Orsay, France).

- Excellent performance of the detector in terms of energy resolution and α/β separation power.
- Positive indications of a good radiopurity of the tested sample.
- A clear thermal neutron capture peak was observed from $^{6}Li(n, \alpha)\,^{3}He$ reaction.

Perspective

To study its radiopurity a long underground run at the Gran Sasso National Laboratory in Italy was performed

An R&D of Li_2MoO_4 crystal scintillators is in progress.
The development of enriched $Li_2{}^{100}MoO_4$ scintillating bolometers is in progress.