Journal of Physics: Conference Series

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To cite this article: M Martínez *et al* 2012 *J. Phys.: Conf. Ser.* **375** 012025

Journal of Physics: Conference Series **375** (2012) 012025 doi:10.1088/1742-6596/375/1/012025

Scintillating bolometers for fast neutron spectroscopy in rare events searches

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Abstract. Neutrons are a relevant background in rare events physics. Detectors based on fast neutron-induced nuclear reactions are commonly used for fast neutron spectroscopy. In this subject, scintillating bolometers provide an excellent energy resolution and particle discrimination by the simultaneous measurement of the heat and emitted light. Our group has constructed several ^{6}Li and ^{10}B based massive scintillating bolometers (LiF, $Li_6Eu(BO_3)_3$, $Li_6Gd(BO_3)_3$), with energy resolutions ranging from 16 to 200 keV. First results of a 32 gr ^{6}LiF scintillating bolometer enriched at 95% in ^{6}Li operated at 20 mK are presented. The use of this material in a multi-target cryogenic dark matter experiment, like EURECA, would allow monitoring the incident neutron flux in the detector during the data-taking.

1. Introduction

Neutron induced nuclear recoils can mimic the WIMP signal in Dark Matter direct searches, so the determination and reduction of the neutron background is mandatory in any experiment of this kind. The expected fluxes in underground laboratories are very weak ($\sim 10^{-6}$ n/cm^2/s for neutrons coming form natural radioactivity in the laboratory rocks and $\sim 10^{-9}$ n/cm^2/s for μ-induced neutrons [1]) and can be strongly reduced with active and passive shieldings. Regarding the neutron background inside the detector, estimations based on Monte Carlo simulations are usually assumed, nevertheless there are always uncertainties (rock composition, veto efficiency, (α, n) reactions in the shielding or the detector itself...) that make it appealing a direct measurement. Between the most practical methods for very low neutron backgrounds spectroscopy are those based on neutron-induced nuclear reactions: the neutron energy is shared between the reaction products and the deposited energy gives directly the incident neutron energy, after subtracting the Q value of the reaction. ^{6}Li and ^{10}B are preferred isotopes due to their relatively high cross-section for neutrons in the range of several MeV (see table 1).

Table 1. Most used neutron-induced reactions for fast neutron spectroscopy.

Reaction (energy at thermal capture)	Q_{value} (MeV)	σ (E_n=1 MeV) (barns)
n+^{3}He$\rightarrow$^{3}H (0.191 MeV) + p (0.574 MeV)	0.765	0.7
n+^{6}Li$\rightarrow\alpha$ (2.050 MeV) + ^{3}H (2.730 MeV)	4.783	0.3
n+^{10}B$\rightarrow$^{7}Li (1.015 MeV) + α (1.777 MeV) (6%) n+^{10}B$\rightarrow$^{7}Li* (0.840 MeV) + α (1.470 MeV) (94%) $\hookrightarrow$^{7}Li + γ (0.48 MeV)	2.792	0.04

The wide target choice and excellent energy resolution achievable with bolometric detectors make them very suitable for this issue. Moreover, in the case of scintillating materials, the particle discrimination power provided by the simultaneous measurement of light and heat produce an almost background-free spectrum, indispensable to measure very weak fluxes. In this work we present the performances of an enriched 32 gr ^{6}LiF for neutron detection and some preliminary results obtained with other interesting materials. Finally, prospects of using these materials in a multi-ton bolometric DM experiment, like the projected EURECA [2], are drawn.

2. LiF bolometers for neutron detector

LiF is an interesting material for bolometric neutron detection: its high Debye temperature makes it suitable as bolometer, and although its scintillation is negligible at room temperature the light emission increases as temperature goes down. The expected efficiency for neutron detection, calculated for a 800 gr cylindrical (h=ϕ) target, is ~20% at ^{6}Li resonance (240 keV), ~4% at 1-2 MeV and ~1% at 6 MeV [1] (see Figs 1 and 2).

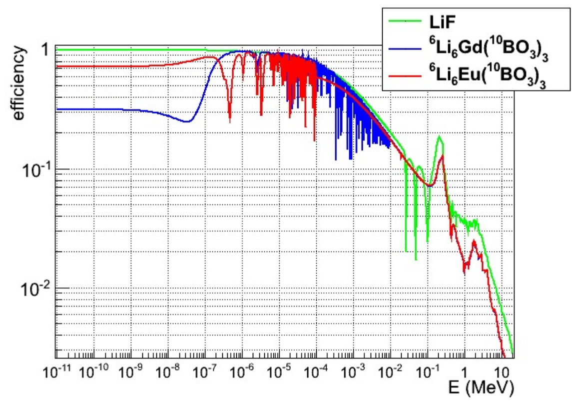

Figure 1. Calculated efficiency of ^{6}LiF, ^{6}Li$_6$Gd(^{10}BO$_3$)$_3$ and ^{6}Li$_6$Eu(^{10}BO$_3$)$_3$ (800 gr, cylindrical shape (h=ϕ), 95% enrichments).

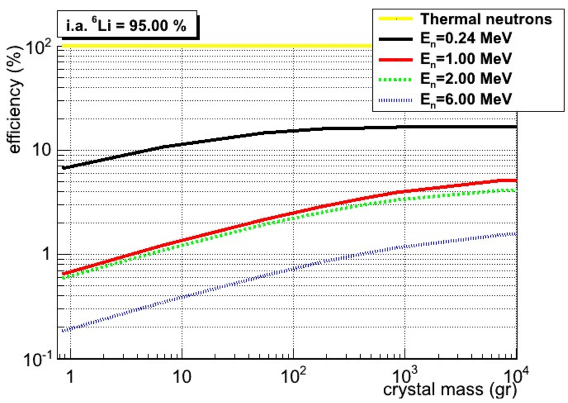

Figure 2. Expected efficiency of ^{6}LiF (95% enriched, cylindrical shape) as a function of the crystal mass.

Since 1993 our group has constructed several LiF bolometers for different purposes [3]. In particular, a 33 gr (not enriched) LiF was tested at the Canfranc Underground laboratory as neutron detector [4]. A portable neutron detector has been constructed, consisting of a small 534 mg ^{6}LiF (95%) (only heat channel) inside a ^{3}He cryostat (active charcoal pumping), with

[1] Multiple scattering is not considered in the calculation, so the given values correspond to lower limits.

an operating temperature of 300-400 mK and an autonomy of around 1 day. The measured energy resolution was 28.7 keV FWHM at the thermal neutrons peak. This detector allowed to demonstrate the energy recovery principle by a dedicated calibration in monoenergetic neutron fields at IRSN AMANDE facility, showing very good energy linearity between 50 keV and 17 MeV (deviation from linearity lower than 3%) [5].

A first prototype 32 gr ^{6}LiF (95%) cylindrical crystal (ϕ=25.1 mm, h=25.2 mm) was tested at sea level and preliminary results are shown in Figs 3 and 4. A lower than expected light yield (3 times lower than that of a 16 gr not enriched LiF [6]) was measured. The thermal/fast neutrons band is well separated from the $\mu/\gamma/\beta$ band down to 2 MeV but not from the α band (estimated with an ^{241}Am source facing the target), preventing a full discrimination of the α background. The energy resolution in the thermal neutrons peak is 50 keV FWHM. The fast neutron spectrum of the non-thermalized ^{252}Cf source is clearly visible in Fig 4 starting from Q_{val}=4.78 MeV.

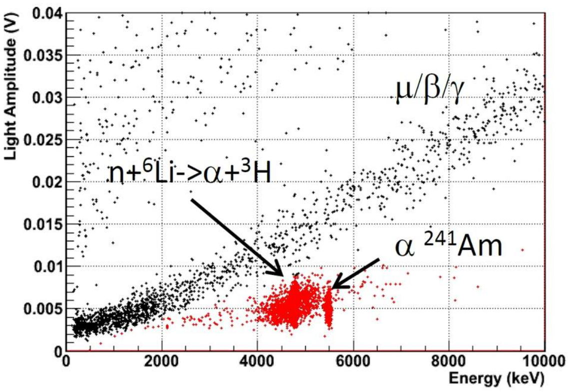

Figure 3. Scattering plot light vs heat of a 32 gr ^{6}LiF (95% enriched). The α/α+^{3}H band (in red) is well discriminated from the $\mu/\beta/\gamma$ band down to 2 MeV.

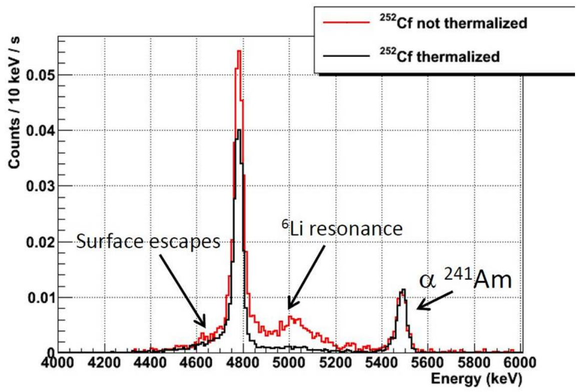

Figure 4. Energy spectra measured by a 32 gr ^{6}LiF (95% enriched) during a ^{252}Cf irradiation. neutron source, thermalized (black line) and non-thermalized (red line).

3. Other ^{6}Li and ^{10}B based materials

The rather poor light yield of LiF encouraged us to investigate other Li and B based scintillators, like the lithium borates LGBO ($Li_6Gd(BO_3)_3$) and $Li_6Eu(BO_3)_3$. Their calculated efficiency for neutron detection is shown in Fig 1 compared to that of LiF, being quite similar (but slightly inferior) in the fast neutron range (but in this case no ^{19}F elastic resonances degrade the efficiency between 10 and 200 keV). On the other hand, efficiency is lower than 1 for thermal neutrons, specially for LGBO (Gd having the higher cross section for thermal neutron capture (^{155}Gd, ^{157}Gd) and following a complicated gamma decay not easy to detect), a fact that could be interesting in certain applications (cleaner fast spectrum near the thermal peak). Only small (5x5x5 mm^3) lithium borate crystals have been tested so far and preliminary results are shown in Figs 5 and 6. Poor light yield and energy resolution were obtained in the case of LGBO (8% FWHM @ 5.49 MeV), but very promising results were found with $Li_6Eu(BO_3)_3$ (not enriched): a collected light yield 10 times better than that from our ^{6}LiF is reported, while 13 keV FWHM resolution is found on the ^{10}B neutron capture peak at 2.31 MeV.

4. Conclusions and prospects

Several ^{6}Li and ^{10}B based scintillating bolometers have been successfully mounted and tested as neutron detectors. Enriched ^{6}LiF has produced very good results, but the current light yield does

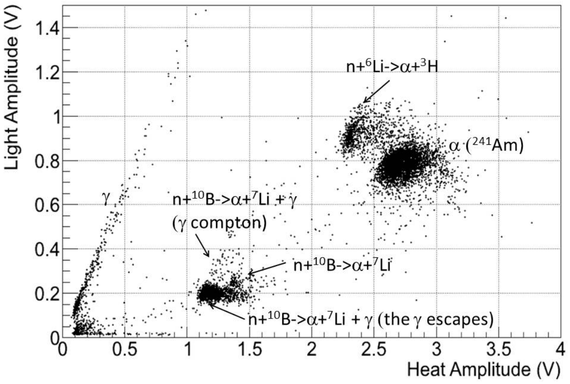

Figure 5. Scattering plot light vs heat of a 5x5x5 mm^3 $^6Li_6Gd(^{10}BO_3)_3$ (95% enriched) during a ^{252}Cf irradiation. Despite the poor resolution, the three reactions (n+^{10}B$\to\alpha$+^{7}Li, n+^{10}B$\to\alpha$+^{7}Li+γ and n+^{6}Li$\to\alpha$+^{3}H) are distinguishable.

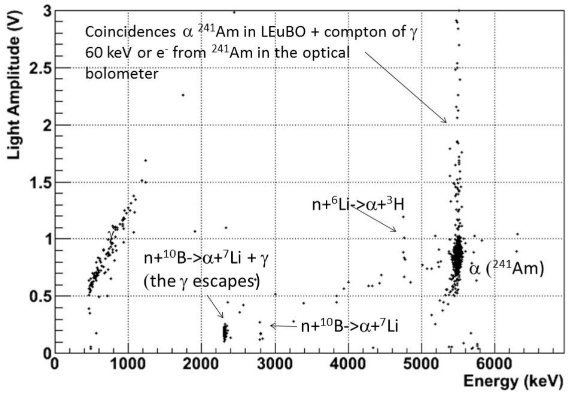

Figure 6. Same as Fig. 6 for a 5x5x5 mm^3 $Li_6Eu(BO_3)_3$ (not enriched). Also in this case the three reactions are well separated despite the poor statistics.

not allow for a full α background discrimination, so other alternatives are being investigated. The use of this kind of materials as targets in a multi-ton DM experiment could provide very interesting information, like the thermal neutron flux at the detectors location (a very valuable input/check for MC simulations), fast neutron detection during neutron calibrations, cross-check of the neutron shielding efficiency in background runs, and fast neutron detection during background runs. Due to the limited efficiency, a certain amount of material is needed to accomplish the last point. For example, to clarify the origin of the current backgrounds in bolometric Ge experiments[2][7] at least 10 kg of ^{6}LiF (95% enriched) would be needed.

Acknowledgments

This work has been supported by the French CNRS/INSU (MANOLIA and BOLERO projects) and by CNES (R&D MOB2). L. Torres is supported by a MICINN postdoctoral grant (Programa Nacional de Movilidad de Recursos Humanos 2008-2011), C. Ginestra by the MICINN Subprograma de Formación de Personal Investigador, and M. Martinez by a postdoctoral grant from the P2I program funded by Université de Paris Sud. We are grateful to Prof. F. Danevich from INR Kiev who kindly provided us with the LiEuBO sample. Partial funding has also been provided by Agence Nationale de la Recherche (ANR) grant SciCryo ANR-05-BLAN-0031.

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[2] Current limits: $\sim$3x10^{-8} pb, corresponding to $\sim$0.01 c/kg/d for energy threshold 10-20 keV (10-20% attributed to neutrons)[7]. Rescaling with Ge neutron elastic scattering cross section and the ^{6}LiF efficiency at $\sim$1 MeV, around 0.001 c/kg/d are expected in ^{6}LiF. This value is a lower limit: elementary kinematics indicate that neutrons producing nuclear recoils under 10-20 keV energy threshold will be easily detected in the LiF detector.