Measurement of the differential neutron flux inside a lead shielding in a cryogenic experiment

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Abstract. The ROSEBUD collaboration measured the differential flux of fast neutrons inside a shielding of lead irradiated with a source of $^{252}$Cf using two scintillating bolometers of LiF and Al$_2$O$_3$ at 20 mK. We compare an unfolding method using a three parameter model for the fast component of the neutron flux with a multigroup method in which the energy interval of interest is divided into groups. Some issues regarding the neutron monitoring with LiF or Al$_2$O$_3$ in a cryogenic experiment searching for dark matter WIMPs are discussed.

1. Introduction

The observation of some events identified as nuclear recoils by experiments using hybrid bolometers for dark matter searches [1, 2, 3] are reported with a careful study of the background sources, in particular the neutron interactions in the involved experimental setups. The hybrid bolometers can separate the nuclear recoils from the electron recoils; but a substantial fraction of the former comes from neutron scattering with the nuclei of the detectors and the remaining, if any, could come from the scattering of dark matter particles. Then, the right estimate of the recoils induced by neutrons and the crosschecking of experimental data with Monte Carlo simulations are issues of paramount importance. Important efforts have been devoted to the measurements of the thermal [4] and muon-induced [5] neutrons in the laboratory, and the beneficial effect of a neutron shielding in a dark matter search was tested underground [6]. In this work we measured with two scintillating bolometers the differential flux of fast neutrons inside a setup similar to a small-scale search for dark matter [7], showing the feasibility of monitoring the fast neutron flux inside the shielding of future dark matter searches with hybrid bolometers. We also stress that besides this monitoring, the positive identification of dark matter would require a signature like the annual modulation of the signal [8, 9, 10, 11] and, furthermore, the events should follow suitable temporal and spatial patterns indicating that mechanical effects as fractures in the bolometers [12] are unlikely.

2. Experimental data and results

We irradiated, in the old Laboratorio Subterráneo de Canfranc, scintillating bolometers of LiF (33 g) and Al$_2$O$_3$ (50 g) inside a lead shielding of 25 cm thickness with a $^{252}$Cf source outside the shielding.
The LiF, through the $^6$Li(n, $\alpha$)$^3$H capture ($Q=4.78$ MeV), is a very interesting target for thermal and fast neutron monitoring [13], because the reaction products give, in the light–heat plot, a signal in a region where the recoils from hypothetical WIMPs are not expected [14, 15]. See in figure 1 the electron recoil events around the straight line passing through (0,0) mV and (1000,500) mV, the nuclear recoil events clustered mainly below (500,100) mV, the captures of thermal neutrons around (2000,400) mV and the resonant captures of fast neutrons around (2100,400) mV. The linearity of the heat signal with respect to the recoil energy is shown in [16]. The Al$_2$O$_3$ detects neutrons only by elastic scattering and it does not distinguish, in principle, neutrons from WIMPs. Figure 2 shows the heat–light plot of Al$_2$O$_3$, where the nuclear recoil events give lower light output than the electron recoil ones.

![Figure 1. Heat–light plot of LiF irradiated with $^{252}$Cf.](image1)

![Figure 2. Heat–light plot of Al$_2$O$_3$ irradiated with $^{252}$Cf.](image2)

The heat signals of Al$_2$O$_3$ were calibrated with a low activity source of $^{57}$Co, assuming that the relative efficiency factor between nuclear and electron recoils is one [17], giving $37\pm9$ keV at the 50 mV discrimination threshold. The heat signals of LiF in the region of the nuclear recoils were not calibrated similarly because the $^{57}$Co peaks were not observed. The calibration with the observed peaks at 2000 mV and 2100 mV [18] gave $160\pm133$ keV at the discrimination threshold of 250 mV. Therefore, the nuclear recoil events of LiF bolometer were not used to estimate the neutron flux.

In a previous analysis [18], assuming the same isotropic neutron flux around both crystals (they were ~20 cm apart), we modeled the neutron energy spectrum with the parameters $\Phi_0$, $\alpha$, $T$: $\Phi(E)dE = \left(\Phi_0/(\Gamma(\alpha+1))\right)(E/T)^\alpha \exp(-E/T) dE/T$ and using MCNP version 4C [19], we found the solution $\alpha=-0.9$, $T=1.48$ MeV and a flux of fast neutrons $\Phi(E > 0.1 \text{ MeV}) = 0.20\pm0.02$ n s$^{-1}$ cm$^{-1}$.

In this work we have applied a more elaborated model based on a multigroup method in which the energy interval of interest is divided into groups. We have assumed that the energy spectrum is a piecewise constant function

$$\Phi(E)dE = \sum_k \Phi_k dE$$

where $\Phi_k \neq 0$ if $E_{k-1} \leq E \leq E_k$ and $\Phi_k = 0$ otherwise. We have chosen six energy groups: (0.05, 0.1), (0.1, 0.2), (0.2, 0.5), (0.5, 1.0), (1.0, 2.0) and (2.0, 5.0) MeV and we have estimated with MCNP–PoliMi [20] the response function of every energy group in both bolometers. After, we have fitted the heat spectra of the events produced by the neutron interactions to a linear superposition of the response functions and we have obtained for every scintillating bolometer the results plotted in figure 3. The experimental data do not give information for energies below 0.1 MeV, the LiF bolometer gives information up to 1.0 MeV and the Al$_2$O$_3$ bolometer up to 5 MeV. Figure 4 shows that
the combined solution (LiF+Al₂O₃), assuming that the neutron flux is the same on both bolometers, is equivalent to the three parameters model.

![Figure 3](image1.png)

**Figure 3.** Estimates of the neutron flux using the model with energy groups to LiF data (solid line) and to Al₂O₃ data (dashed line)

![Figure 4](image2.png)

**Figure 4.** Comparison of the combined solution (LiF+Al₂O₃) obtained with six energy groups (histogram) and the obtained with the three parameters model (continuous line).

In order to crosscheck our results, we have estimated with MCNP-PoliMi the absorption spectrum in LiF (figure 5) and the nuclear recoil spectrum in Al₂O₃ (figure 6) produced by a fast neutron flux inside the shielding using the solution of the three parameters model ($\alpha=-0.9$ and $T=1.48$ MeV), with the total flux as a free parameter for each bolometer. The experimental and simulated spectra are in good agreement in both bolometers; the fast neutron fluxes ($E > 0.1$ MeV) are $0.218\pm0.016$ and $0.204\pm0.025$ n s⁻¹ cm⁻² for LiF and Al₂O₃, respectively, indicating that the model with three parameters describes quite well the neutron flux. Similar results are obtained with the model with six energy groups.

![Figure 5](image3.png)

**Figure 5.** Experimental and simulated spectra of absorbed fast neutrons in LiF. The peak corresponding to the capture of thermal neutrons (~2000 mV) is not shown.

![Figure 6](image4.png)

**Figure 6.** Experimental and simulated spectra of nuclear recoils in Al₂O₃. The $^{57}$Co calibration gave $37\pm9$ keV at the discrimination threshold at 50 mV.

3. Conclusions

We have measured inside a shielding of lead the differential flux of fast neutrons ($E > 0.1$ MeV) coming from a $^{252}$Cf source placed outside the shielding. The source produced a rate of $1.7\times10^7$ captures $y^{-1}$ kg⁻¹ of LiF around the resonance at 0.24 MeV, and the estimated flux of fast neutrons ($E > 0.1$ MeV) on the bolometers was 0.2 n s⁻¹ cm⁻². A simple scaling law indicates that a flux of $2\times10^{-9}$ n s⁻¹ cm⁻² with similar energy dependence can be monitored by 100 kg of LiF or by
10 kg of enriched $^6$LiF, giving ~20 captures y$^{-1}$. The analysis of the response of LiF to fission neutrons from internal sources is in progress.

The neutron monitoring with LiF of a dark matter search could be better if the nuclear recoils of LiF were well calibrated and its discrimination threshold was low enough; in this case, the compatibility of capture and elastic scattering of neutrons could be tested within the same detector, not with another near detector.

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