

Light yield of undoped sapphire at low temperature under particle excitation

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Abstract

In this letter, we report on the performance of scintillating sapphire bolometers developed in the framework of the ROSEBUD (Rare Objects Search with Bolometers UnDerground) Collaboration devoted to dark matter searches. The simultaneous measurement of heat and light allows the discrimination of the type of particle increasing the sensitivity for these searches. A heat versus light negative correlation for gamma events has been observed. Its interpretation, in a simple framework, allows the estimation of the light yield of undoped sapphire at a temperature of about 20 mK under gamma, alpha and neutron excitation.

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Pure and doped aluminium oxides are currently being investigated in depth and have been successfully applied in a variety of fields (optical windows, lasers, dosimetry, particle detection, etc.) due to their thermal, mechanical and optical properties. Concerning particle detection, sapphire has been taken as a long wavelength scintillator¹ and as a bolometer²⁻⁴. Our collaboration has used⁴ undoped sapphire as a bolometric target in the search for Weakly Interacting Massive Particles (WIMPs) which are supposed to compose a large fraction of the Universe matter budget. In such bolometric devices the energy released by a particle interaction (typically in the range from keV to MeV) is measured as a temperature increase by a convenient thermometer. In a scintillating bolometer the simultaneous measurement of heat and light allows particle discrimination⁵⁻⁷ based on the strong dependence of scintillation on the density of the energy deposition: electrons and photons produce much more light than neutrons or WIMPs delivering the same energy in the target while the response in the form of heat is similar. The active background rejection of such devices increases strongly the sensitivity for WIMP searches and led to the development of scintillating CaWO_4 bolometers⁸⁻⁹. Recently, some of the authors¹⁰ have reported that undoped sapphire scintillates and, at very low temperatures (about 20 mK), has a strong light yield relative to other well known scintillators like CaWO_4 or BGO. Scintillation of undoped sapphire, which could be attributed to the presence of impurities (in accordance with the observation of an enhancement of luminescence for low concentration Ti-doped sapphires¹¹), reinforced our interest in sapphire as a WIMP direct detection target and, consequently, scintillating sapphire bolometers have been developed and tested.

Measurements have been performed at Orsay with a double bolometer operating at 20 mK that simultaneously measures heat and light. It consists of a 50 g undoped

scintillating Al_2O_3 crystal (grown by the Kyropoulos GOI method, with a Ti content lower than 10 ppm in weight) and a small Ge crystal (25 mm diameter, 100 μm thickness), for detection of scintillation photons, inside a silver-coated reflecting cavity (see Fig. 1). The heat produced in the Al_2O_3 crystal is directly seen as a temperature increase (heat channel) and the emitted light escaping from it is eventually absorbed in the Ge crystal where it is also converted into heat (light channel). Both heat signals are finally measured by the corresponding Neutron Transmutation Doped Ge thermistors whose voltage outputs (OR triggered) are digitized and analyzed off-line. An inner ^{55}Fe x-ray source is placed opposite the Ge bolometer to calibrate the energy absorbed in the form of light. Both channels are calibrated with an internal encapsulated ^{241}Am gamma source facing the sapphire crystal and external gamma (^{57}Co) and neutron (^{252}Cf) sources.

Figure 2 shows the light versus heat pulse amplitudes obtained in a ^{57}Co calibration. The band of lower light response corresponds to nuclear recoil events (confirmed in calibrations with the ^{252}Cf source), in this case mostly produced by environmental neutrons. The ratio between β/γ and neutrons light output, estimated to be 17.5 ± 1.5 at 200 keV, is usually taken as a measurement of the discrimination capability; just as reference some values reflect the excellent performance of sapphire: 10 (CaWO_4)⁹ and 12-15 (BGO)¹⁰. The lines at 59.5, 122.1 and 136.5 keV, corresponding to gamma events from ^{241}Am and ^{57}Co sources, show a negative correlation between light and heat pulse amplitudes (see Figure 2 and Table I) never observed with any scintillating bolometer. It can be used to improve the resolution of each gamma line in the heat channel, but not of the whole spectrum due to the

correlation energy dependence (see Fig. 2). In fact, the poor resolution previously obtained in sapphire bolometers measuring only heat²⁻⁴ is probably due to this effect.

A quantitative interpretation of this correlation that allows the estimation of the light yield of the undoped sapphire is presented hereafter. Using mean voltage values $\langle V \rangle$ of the three lines (see Table I), we have performed a linear calibration of the deposited energy E (keV) = $a \langle V \rangle + b$ for each channel, giving $a_h = 0.0511 \pm 0.0001$ keV/mV, $b_h = -1.9 \pm 0.3$ keV and $a_\ell = 0.118 \pm 0.001$ keV/mV, $b_\ell = 6.1 \pm 0.9$ keV in the heat and light channels, respectively. Assuming that, when a gamma particle interacts in the sapphire crystal, on average, a fraction α_h of the deposited energy is initially converted into heat and a fraction α_ℓ into light ($0 < \alpha_h < 1$; $0 < \alpha_\ell < 1$) the mean voltage outputs in the heat and light channels are given by

$$\begin{aligned} \langle V_h \rangle &= g_h \alpha_h E + g'_h \\ \langle V_\ell \rangle &= g_\ell \alpha_\ell E + g'_\ell \end{aligned} \quad (1)$$

being g the gains, g' the offsets of the corresponding channels, and ε the light collection efficiency. It follows that

$$a_h/a_\ell = (g_\ell \varepsilon \alpha_\ell) / (g_h \alpha_h) = 0.433 \pm 0.004, \quad (2)$$

where the numerical value has been estimated from the above mentioned energy calibrations.

Assuming an energy transfer E_x from one channel to the other inside the sapphire crystal (with mean zero and variance σ_x^2) the output voltage signals consist of an independent term (subscript i) and a correlated one

$$\begin{aligned} V_h &= V_{hi} + g_h E_x \\ V_\ell &= V_{\ell i} - g_\ell \varepsilon E_x. \end{aligned} \quad (3)$$

A possible origin of the negative correlation effect is the presence of inhomogeneities in the sapphire crystal that could produce a light yield or self-absorption of scintillation photons in the sapphire (see discussion below) depending on the site of the energy deposition. Regardless the cause, the final effect in a peak is described as having in the heat (light) signal a Gaussian distribution V_{hi} ($V_{\ell i}$) of mean $\langle V_h \rangle$ ($\langle V_\ell \rangle$) and variance σ_{hi}^2 ($\sigma_{\ell i}^2$) plus a Gaussian distribution of mean zero and variance $\sigma_{hx}^2 = g_h^2 \sigma_x^2$ ($\sigma_{\ell x}^2 = g_\ell^2 \varepsilon^2 \sigma_x^2$), so that the total variance observed in the heat (light) channel is $\sigma_h^2 = \sigma_{hi}^2 + \sigma_{hx}^2$ ($\sigma_\ell^2 = \sigma_{\ell i}^2 + \sigma_{\ell x}^2$). The correlation between V_h and V_ℓ is given by

$$\rho = \frac{1}{\sigma_h \sigma_\ell} \frac{\partial V_h}{\partial E_x} \frac{\partial V_\ell}{\partial E_x} \sigma_x^2 = - \frac{g_h g_\ell \varepsilon \sigma_x^2}{\sigma_h \sigma_\ell} = - \frac{\sigma_{hx} \sigma_{\ell x}}{\sigma_h \sigma_\ell} \quad (4)$$

From the experimental values of σ_h , σ_ℓ and ρ (see Table I) we can draw estimates for σ_{hx} and $\sigma_{\ell x}$. Taking into account that $\sigma_{hx} < \sigma_h$ and $\sigma_{\ell x} < \sigma_\ell$, we have considered the two extreme cases (for $\sigma_{hx} = \sigma_h$ and for $\sigma_{\ell x}$ the minimum value derived from equation 4, and viceversa) in order to bind σ_{hx} and $\sigma_{\ell x}$. In Table I we have quoted for σ_{hx} and $\sigma_{\ell x}$ the mean of these two extreme values and estimated the systematic error of our method

as being half the difference between them. Since the ratio of calibration slopes a_h/a_ℓ depends on the magnitudes α_ℓ and α_h , and the correlation effect does not depend on them, these two magnitudes can be estimated from a_h/a_ℓ and ρ (equations 2 and 4). In particular, $\sigma_{\ell x} / \sigma_{hx} = (g_\ell \varepsilon) / g_h$ and therefore the ratio $q \equiv (a_h/a_\ell) / (\sigma_{\ell x} / \sigma_{hx})$ is an estimator for α_ℓ / α_h . If the total deposited energy initially goes into heat or light, that is, $\alpha_\ell + \alpha_h=1$, we can derive the value of the mean light yield (for instance, $\alpha_\ell = 0.127 \pm 0.010$ for β/γ particles of 122.1 keV). Notice that the three analyzed lines give values which are compatible with the assumption of a mean light yield independent of the energy in the surveyed range in spite of the fact that correlation grows with energy (see Table I). The 59.5 keV line has a large systematic error due to its low correlation compared to that of the 122.1 and 136.5 keV lines. The energy calibration of the optical bolometer (performed with the ^{55}Fe x-ray source) allows to estimate an upper limit for the light collection efficiency, ε , assuming that all the x-ray energy is converted into heat in the Ge disk (Note that thermalization in semiconductors can be limited by energy lost to trapping as reported in reference 12 for doped Ge thermistors). For each MeV released by gamma particles, an equivalent light energy of 13.5 ± 0.3 keV has been measured. Since the emitted light energy is $\alpha_\ell E$, a value of about 10% for ε in our configuration is derived (for instance, $\varepsilon \leq 0.106 \pm 0.009$ from 122.1 keV events). We have estimated a mean light yield of 0.0073 ± 0.0010 for neutrons by dividing the β/γ light yield by the ratio of the β/γ to neutrons light output.

Assuming that on average a fraction κ ($0 < \kappa < 1$) of the scintillation photons is absorbed in the sapphire crystal (up to now we have considered $\kappa=0$) and considering the variation of self-absorption as the only cause of the observed light versus heat

correlation, estimates of α_ℓ rescale with a factor $1 / (1 - \kappa)$. Another modification could come from the consideration of an additional channel for the energy deposited, (for instance, energy stored in traps, a known feature of pure and doped sapphire at room temperature). If there is a fraction of energy α_o not going into heat or light within our milliseconds range integration time, $\alpha_\ell + \alpha_h + \alpha_o = 1$, and estimates of α_ℓ rescale with a factor $1 - \alpha_o$.

To investigate the negative correlation, another undoped 50 g scintillating sapphire crystal (from the same origin) with an inner ^{210}Po source was tested. External ^{57}Co and ^{137}Cs sources were used to verify the behaviour of the correlation at gamma energies up to 661.7 keV and the ^{210}Po source was used to analyze the light yield under alpha particle excitation. On the one hand, a negative correlation between light and heat pulse amplitudes for gamma events, increasing again with energy, was observed. The values derived for α_ℓ ($0.16 \pm 0.01_{\text{stat}} \pm 0.07_{\text{syst}}$ and $0.16 \pm 0.02_{\text{stat}} \pm 0.04_{\text{syst}}$ at 122.1 keV and 661.7 keV, respectively) are similar to those of the other bolometer and compatible again with the independence of α_ℓ on the energy. On the other hand, a ratio between β/γ and alpha particles light output of 10.3 ± 1.0 is obtained, giving an estimate of the mean light yield for alpha particles of $0.016 \pm 0.002_{\text{stat}} \pm 0.004_{\text{syst}}$ which implies a small negative correlation of about 10^{-2} for monoenergetic alpha particles. The full alpha peak from ^{210}Po (5.3 MeV) showed a small positive correlation $\rho=0.303 \pm 0.014$; however, $\rho=0.051 \pm 0.032$ (consistent with the expected value) is obtained when taking only the upper half of the peak. These results can be understood if the peak has a contribution from energy degraded (probably in the source itself) events.

Undoped sapphire crystals at very low temperature are being investigated as scintillating bolometers and are foreseen for the next dark matter searches at the Canfranc Underground Laboratory (Spanish Pyrenees). A light versus heat negative correlation for gamma events has been observed. Light yield of undoped sapphire under particle excitation at very low temperature has been estimated with an original method based on this correlation effect: assuming no energy lost to trapping, values of 0.127 ± 0.010 , 0.016 ± 0.004 and 0.0073 ± 0.0010 for photons, alpha particles and neutrons, respectively, have been derived. Further research is still in progress.

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TABLE I. Main parameters of the light versus heat response of undoped sapphire to ^{57}Co and ^{241}Am gamma sources. Subscripts h and ℓ represent heat and light, respectively, and x represents their correlated terms. $\langle V \rangle$ is the mean voltage, σ its standard deviation, ρ the correlation between light and heat output voltages, α_ℓ and α_h are the mean light and heat yields.

Energy (keV)	59.5	122.1	136.5
$\langle V_h \rangle$ (mV)	1202.3	2424.4	2709.7
$\langle V_\ell \rangle$ (mV)	451.2	975.7	1103.3
σ_h (mV)	12.1 ± 0.3	26.2 ± 0.4	29.2 ± 1.1
σ_ℓ (mV)	47.0 ± 1.0	77.5 ± 1.2	85.4 ± 3.3
ρ	-0.61 ± 0.02	-0.890 ± 0.005	-0.87 ± 0.01
σ_{hx} (mV)	$9.7 \pm 0.3_{\text{stat}} \pm 2.3_{\text{syst}}$	$24.7 \pm 0.4_{\text{stat}} \pm 1.4_{\text{syst}}$	$27.3 \pm 1.1_{\text{stat}} \pm 1.9_{\text{syst}}$
$\sigma_{\ell x}$ (mV)	$37.8 \pm 1.1_{\text{stat}} \pm 9.1_{\text{syst}}$	$73.2 \pm 1.2_{\text{stat}} \pm 4.2_{\text{syst}}$	$79.8 \pm 3.3_{\text{stat}} \pm 5.5_{\text{syst}}$
α_ℓ / α_h	$0.111 \pm 0.006_{\text{stat}} \pm 0.037_{\text{syst}}$	$0.146 \pm 0.004_{\text{stat}} \pm 0.012_{\text{syst}}$	$0.148 \pm 0.009_{\text{stat}} \pm 0.015_{\text{syst}}$
α_ℓ	$0.100 \pm 0.005_{\text{stat}} \pm 0.030_{\text{syst}}$	$0.127 \pm 0.003_{\text{stat}} \pm 0.009_{\text{syst}}$	$0.129 \pm 0.007_{\text{stat}} \pm 0.011_{\text{syst}}$

Figures

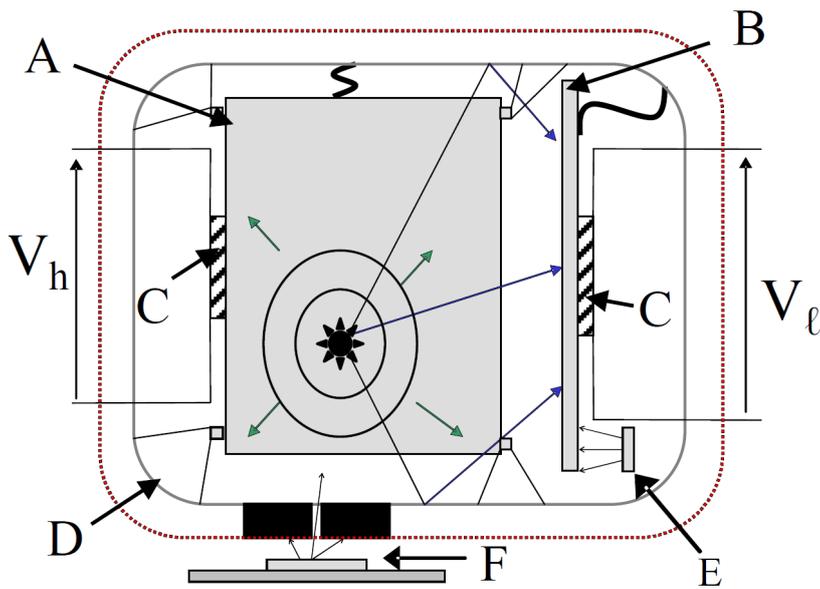


FIG. 1. Scheme of the double bolometer: (A) 50 g scintillating sapphire, (B) Ge optical detector, (C) thermistors, (D) reflecting cavity, (E) ^{55}Fe source, and (F) ^{241}Am source.

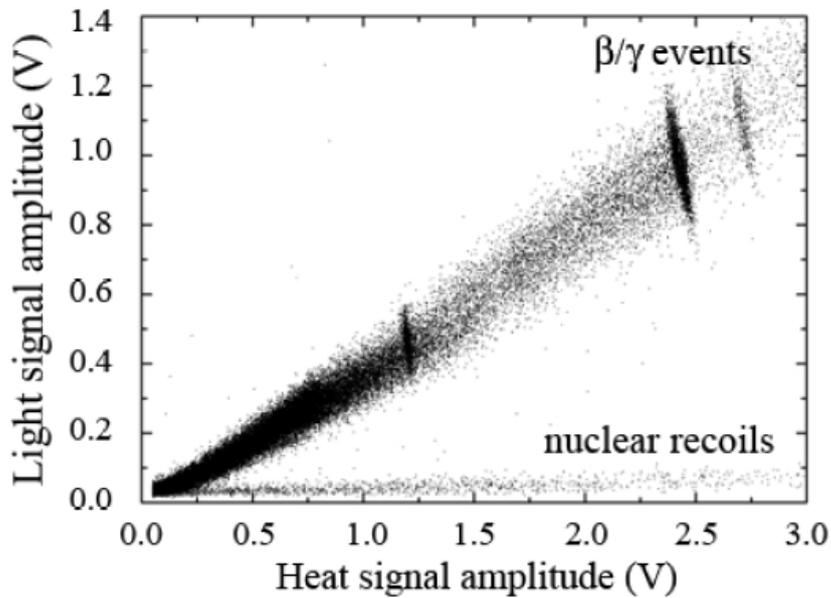


FIG. 2. Light versus heat discrimination plot for a ^{57}Co calibration. Discrimination between β/γ events and nuclear recoils is evident. The lines at 59.5 keV (from an internal ^{241}Am source) and 122.1 and 136.5 keV are clearly seen in the β/γ band at values (in the heat channel) around 1.2, 2.4 and 2.7, respectively.