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Development of 3d printable scintillating plastic for bolometric $0\nu\beta\beta$ decay experiments

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The 3dSPARK (3d-printed Scintillating Polymer Assembly for Rare Events at milliKelvin temperature) project aims to develop a novel type of assembly for next-generation bolometric neutrinoless double beta decay experiments. A significant part of the background in bolometric experiments originates from contamination of the copper frames traditionally used in the assembly. By using a 3d-printed polymer-based mechanical structure, whose design can be highly optimised thanks to the flexibility of additive manufacturing, the mass is reduced, and the gamma interaction probability is lowered due to the material's low atomic number. Additionally, this approach enables the structure to function as an active veto by incorporating a scintillating compound, which can ultimately help to further reduce the background contribution from the detector structure. We report an overview of the project and show the potential of this technology to decrease the background level, as demonstrated by Geant4 simulation studies. We also present our first results on the optical characterisation of a 3d scintillating plastic.

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1. Introduction

Cryogenic calorimeters are one of the most promising technologies for the discovery of the neutrinoless double beta decay ($0\nu\beta\beta$) [1, 2]. These are able to measure the energy released by particles at milli-Kelvin temperatures with an excellent energy resolution, embedding the isotope of interest, leading to high detection efficiency. One of the main experimental challenges related to this technique is the ability to maintain many crystals at cryogenic temperatures. Copper holders are widely used in bolometric $0\nu\beta\beta$ experiments for their mechanical response at the milli-Kelvin scale and their high thermal conductivity [3–6]. Thus, they act both as a mechanical support and a thermal link to the cryostat, providing the cooling power required to keep the detectors at the working temperature. Nevertheless, the passive nature, high density and high Z of these structures induce a non-negligible background in the experiments. The majority of the β/γ background observed in the CUORE experiment [3], which studies the $0\nu\beta\beta$ of ^{130}Te ($Q_{\beta\beta}$ = 2527.5 keV), is coming from high-energy γ particles undergoing Compton scattering in the passive elements of the setup. In particular, the 2.6 MeV γ of the ^{208}Tl from the ^{238}U decay chain can interact in the copper and deposit its remaining energy in the region of interest. Thus, having a low Z and low-density material would decrease the probability of interaction in the holders and decrease the background. On the other side, the copper has internal contamination from the natural radioactivity of the ^{238}U and ^{232}Th decay chains, which can typically be at a level of a few μBq/kg, which is for now not a major background, but could still be decreased with a lower mass structure. On the contrary, the surface contamination of the copper holders is expected to be one of the dominant backgrounds for the next-generation bolometric experiment CUPID [7]. CUPID will study the $0\nu\beta\beta$ of ^{100}Mo ($Q_{\beta\beta}$ = 3034 keV), with scintillating crystals, allowing for α particle discrimination. The background will be thus coming from the β/γ particles emitted by the ^{208}Tl and ^{214}Bi of the ^{238}U and ^{232}Th decay chains. In CUORE, the copper pieces were contaminated at a level of ~10 nBq/cm [8]. In CUPID, such a level of contamination would produce a background of $\sim 4 \times 10^{-5}$ counts/keV/kg/yr in the region of interest [9, 10] which corresponds to ~ 40% of the CUPID background budget.

Copper may, therefore, not be an optimal choice from the background point of view. Moreover, the next-to-next-generation experiment will need to decrease further the background to probe the normal ordering of the neutrino mass, thus, the exploration of new materials for the detector structure becomes fundamental.

2. The 3dSPARK project

The 3dSPARK project aims to develop a 3d printable scintillating polymer assembly for $0\nu\beta\beta$ experiments. The 3d printable polymer has a low Z, allows for versatility in the shapes, and is relatively cheap. The polymers have, in general, a low level of internal contamination [11], while they should not present any surface contamination thanks to the 3d printing method.

As previously mentioned, such a structure is of great interest for the search of the $0\nu\beta\beta$ of the ^{130}Te even without the scintillation. A study based on Geant4 simulations showed that a passive polymer-based assembly could decrease the level of background coming from the holders and the other sources external to the crystals by a factor of 5 [12].

In future stages of the CUPID program [13], following the CUPID experiment, the objective will be to reduce the background contributions from the frames by at least one order of magnitude compared to the current CUPID background budget. Achieving this reduction would enable the CUPID successors to further explore the normal ordering region. One approach to achieve this is through scintillation of the polymer structure, which enables its operation as an active veto. Figure 1 shows a schematic depiction of the most relevant topologies which can produce a background in the CUPID experiment and can be suppressed by the use of a scintillating polymer-based structure. In all cases, only part of the original particle energy is deposited in the crystals, while the remaining energy is absorbed in the surrounding structural elements. The scintillation light coming from the plastic could be read by the Ge cryogenic light detectors used to read the scintillation light from the crystals in CUPID or by an optical fibre that could collect the light and guide it outside of the cryostat to be read at room temperature.

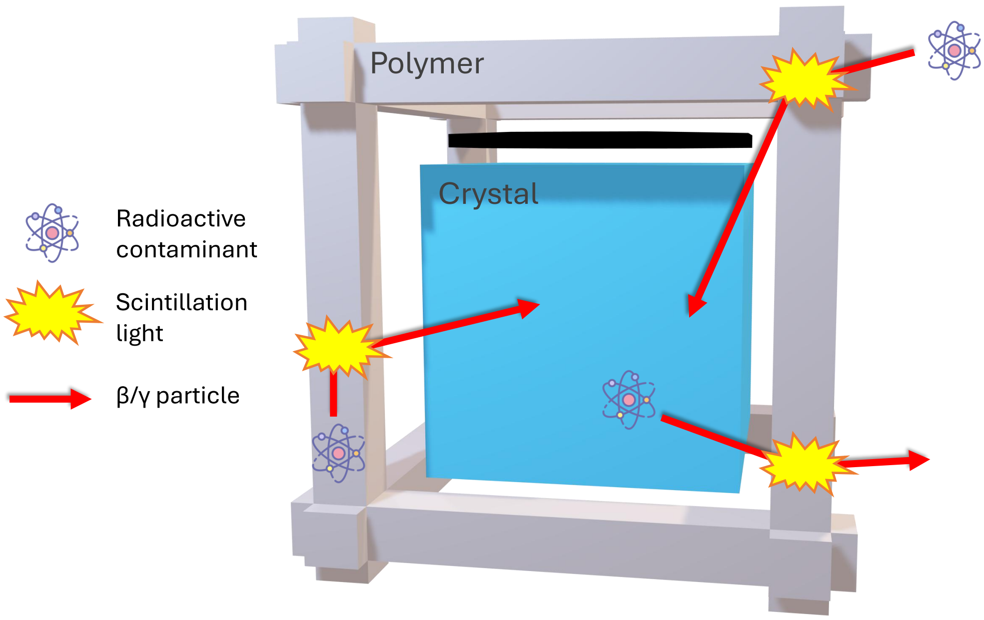

Figure 1: Scheme of the backgrounds which can be observed in CUPID and suppressed with the use of a scintillating polymer assembly, thanks to the simultaneous read-out of the heat in the crystal and the scintillation of the holders as in the 3dSPARK project. In the CUPID experiment, Ge wafers are used as bolometric light detectors (black) to read the scintillation of the crystals. In the 3dSPARK project, the scintillation of the polymer could be either measured by these same light detectors or guided through a fibre to be read outside the cryostat at room temperature.

Another key aspect of the project is demonstrating the ability to cool the crystals and light detectors effectively. Copper is commonly employed due to its favourable thermal properties. However, cooling with a polymer-based assembly has already been demonstrated for small crystals in [14], where thermal conduction was achieved via the connecting wires.

3. Geant4 simulations

To explore the impact of such assembly, we performed simulations of the CUPID experiment, replacing the copper with PMMA, with Geant4 [15]. We recorded the energy deposited in the crystals, light detectors, and the PMMA frames. We didn't simulate the scintillation in Geant4, but generated it in a post-simulation step. For the scintillation of the crystals, it is based on experimental data as done in the CUPID background projections [9]. For the scintillation of the plastic, we assumed a measured light yield of 100 photons/MeV and a detection threshold of 3 photons. With such parameters, and assuming that the PMMA has the same levels of contamination as the copper in CUORE, we can decrease the background coming from the frames up to a factor of 7, while decreasing the background from the crystals up to a factor of 3. The impact on the other, most external sources, is negligible. These light performances are quite conservative, improving them could lead to a reduction by a factor of 10 in the contribution of the frames.

Volume	Background reduction factor
Crystal	3.1 ± 1.8
Holders	7.4 ± 1.5

Table 1: Background reduction factors with respect to CUPID assuming a scintillating polymer assembly with a detected light yield of 100 photons/MeV and a detection threshold of 3 photons.

In the future, we plan to perform the scintillation simulation within Geant4, to optimise the detector setup and study the possibility of reading the plastic scintillation with the Ge light detectors.

4. Optical characterisation of the scintillating plastic

As a first attempt at a 3d scintillating material, we chose to use the commercial Clear Resin V4, from FormLabs. The resin itself doesn't scintillate, the principle is to add a scintillating dye to be diluted in the resin and then 3d printed. We used a concentration of the dye in the polymer of 5×10^{-4} in mass, which corresponds to 0.37 mg/mL, which was the maximum achievable concentration before the dye does not dilute anymore.

We performed an absorbance measurement of a cylindrical 3d printed sample as well as a radioluminescence measurement, as shown in the figure 2. There is an absorbance (blue spectrum) at wavelength < 400 nm coming from the resin, which is expected from polymers in general, as for example the PMMA. There is also a double peak of absorbance between 400 and 500 nm, which is coming from the scintillating dye. On the radioluminescence side (orange spectrum), there is a small emission peak around 420 nm, coming from the resin itself and which is absorbed by the dye. The emission of the dye is peaked at 550 nm and is well separated from the absorption spectrum. This means that the self-absorption should be small, and that this material can be of interest for scintillation in our application.

We then measured the light yield induced by particles interacting in the polymer, coupling the cylindrical sample to a SiPM with an optical grease. We performed measurements with various sources, including an alpha source of ^{241}Am, producing also some low-energy γs, and β sources of ^{90}Sr-Y and ^{99}Tc. We could not observe any clear hint of scintillation for none of the sources. This

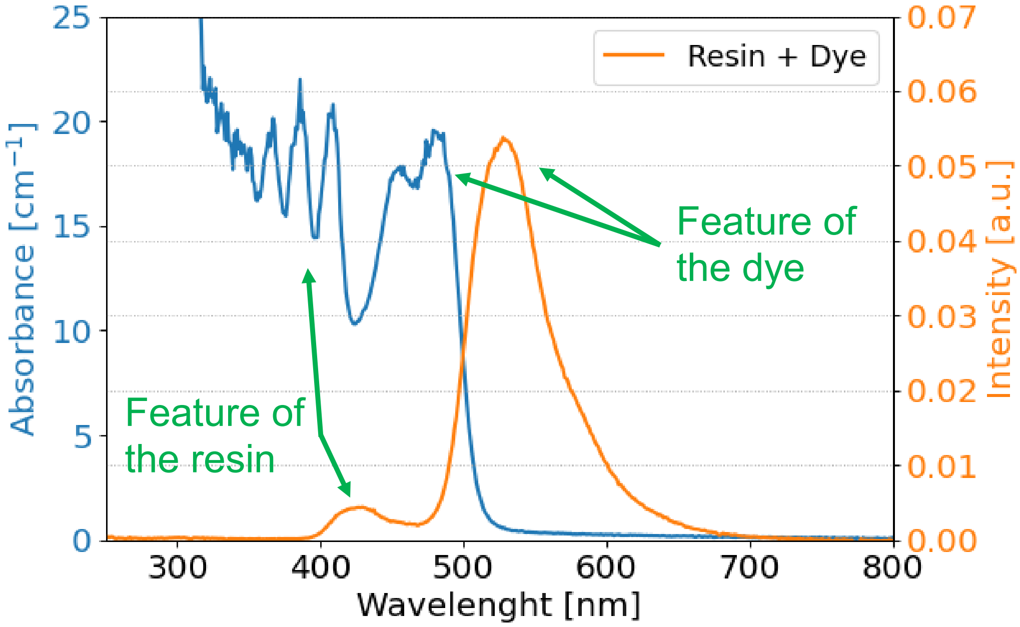

Figure 2: Absorbance (blue) and radioluminescence (orange) spectra of the Clear Resin V4 with a scintillating dye with a concentration of 5×10^{-4} in mass. We observe various structures characteristic of the polymer and the scintillating dye.

could indicate that the concentration of the dye was not high enough, or other issues related to the energy levels of the resin itself, not being able to transfer the energy deposited in the matrix into the scintillating dye.

5. Perspectives

We plan to test different scintillating compounds to be added to the polymer with various concentrations. One key point is that it is not possible to dilute high concentrations in the Clear Resin V4, which is an acrylic. For this reason, we may also try other types of polymer and/or add other solvents to increase the solubility of the dye in the mixture, as done in [16].

Finally, the project goal is to run a prototype tower with crystals of the size of the CUPID ones, and demonstrate that they can be cooled down with such a polymer assembly, reaching the standard detector performance, and that we are able to read a scintillation light signal from the frames, being compatible with the background rejection goals.

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