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Organic compounds for rare events physics

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Summary. — The neutrinoless double-beta decay background in TeO_2 calorimetric searches receives two main contributions. One comes from α surface contamination and the other is mainly due to 2615 keV γ's, from the ^{232}Th chain, scattering Compton with materials close to the detectors. In order to reduce the latter γ component, we propose to replace the usual copper holders with structures made of light organic compounds. A polymethylmethacrylate (PMMA) holder, containing small TeO_2 crystals, is operated in a cryogenic setup, together with a similar assembly made of copper. The former registers a lower background in the Region of Interest (RoI), when exposed to a ^{232}Th source, with a $3.8\,\sigma$ significance. The background reduction of the setup is in agreement with Monte Carlo simulations at $1.2\,\sigma$. Then, a more realistic application is considered by simulating the inner CUORE experiment structure made of PMMA. We obtain a γ background reduction factor of $4.7^{+0.5}_{-0.6}$ for photons coming from environmental sources and $5.0^{+0.1}_{-0.2}$ for near detector contaminations with respect to the same setup made of copper.

1. – Introduction

Neutrinoless double-beta decay ($0\nu\beta\beta$) [1, 2] is a second-order process proposed in the framework of Beyond SM physics. It is, until now, the only direct tool to probe the neutrino Majorana nature. It is also important to study lepton number violation and neutrino masses together with their hierarchy. One of the most promising approaches to this decay search makes use of thermal detectors made of TeO_2. In this case, ^{130}Te is the main $\beta\beta$ emitter and its Q-value ($Q_{\beta\beta}$) is of about 2527 keV, where the $0\nu\beta\beta$ peak is expected.

Being the $0\nu\beta\beta$ an extremely rare event, a low background in the Region of Interest (RoI), defined as the energy region around the Q-value, is an experimental prerogative. CUORE [3], a world leading experiment in terms of ^{130}Te $\beta\beta$ decay, is characterized by a uniform background in the RoI equal to $B = 1.38 \times 10^{-2}\,\frac{\text{counts}}{\text{keV}\cdot\text{yr}\cdot\text{kg}}$ [4]. Future-generation experiments aim at lowering it by 2–3 orders of magnitude. The CUORE background is dominated (90%) by α surface contamination of materials in the detector vicinity. Approaches to reduce this contribution consist in using cleaner materials, exploiting detector light readout and adding vetoing elements.

We focus on the remaining γ component (10%). It is mainly due to ^{208}Tl de-excitation 2615 keV photons, coming from environment ^{232}Th contaminations in the near detector material. They can undergo Compton scattering with holders around detectors and, losing a small fraction of their energy, they can contribute to the RoI background.

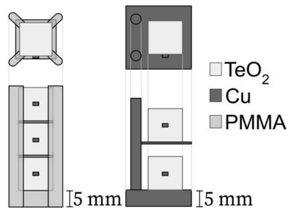

Fig. 1. – Sketch of the two towers containing the TeO_2 crystals. On the left the PMMA assembly, on the right the copper one.

In this work, we propose to replace the usual copper components close to the crystals with organic compounds. In particular we consider holders made of polymethylmethacrylate (PMMA). Photons have a lower Compton scattering cross-section with this material, thanks to its low atomic number and density, respectively $Z_{eff} = 6.5$ and $\rho = 1.18$ g/cm^3. PMMA is already produced for ultra-low background purposes, with ^{232}Th and ^{238}U specific activities at the level of the cleanest CUORE copper [5, 6]. PMMA can also be 3D printed, allowing to build complicated structures, if needed. Moreover, this organic compound can be easily used as scintillator [7], turning the holders into active components to veto radiation.

In order to quantify the RoI background reduction due to a PMMA holder, we operated in a cryogenic environment two similar assemblies, one made of PMMA and the other made of copper, as reference. The experimental setup, briefly described in sect. **2**, has been exposed exposed to a ^{232}Th calibration source. In sect. **3**, we show the results and the comparison between the background obtained from the two different material holders. Furthermore, we extrapolate the effect of the material replacement in a more realistic experimental configuration: the CUORE inner detector. We simulate its structure and the most relevant γ contaminations and we report the RoI background reduction factors. For a more detailed description of the experimental setup and the analysis steps described in the next sections, refer to [8].

2. – Setup and Monte Carlo simulation

Measurements have been performed in the cryogenic laboratory of Milano-Bicocca University. Two similar towers, shown in fig. 1, have been assembled. They contained $1 \times 1 \times 1$ cm^3 TeO_2 crystals, each of them equipped with a Neutron Transmutation Doped Ge thermistor (NTD) glued on a side. The NTD produces an electric signal when some energy is deposed in the TeO_2 crystal. The obtained signal was amplified, Bessel-filtered and, finally, digitized by means of a 16-bit ADC. The two assemblies have been installed and wired into an Oxford ^{3}He-^{4}He dilution cryostat. Their operating temperature was maintained at ~ 10 mK. A calibration source was placed below the cryostat outer vacuum chamber. The two towers were surrounded by a lead shield to protect them from environmental γ. We have also reproduced the setup structure in a Monte Carlo simulation. As can be seen in fig. 2, besides the holding structures and the source, only the relevant parts of the cryostat setup have been included. They, indeed, represented the only target components for a 2615 keV γ falling in the experimental RoI after Compton scattering with them. From now on, the RoI will be defined as the energy region with a total width of 50 keV and centered at the ^{130}Te decay $Q_{\beta\beta}$.

3. – Data analysis and results

Some calibration runs have been collected during the cool-down. The ADC boards digitized and stored a continuous stream of data from each channel. A derivative trigger

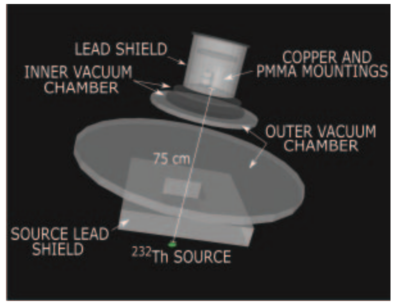

Fig. 2. – 3D rendering of the experimental setup. It has been employed for the Monte Carlo simulation.

flagged pulses which were extracted in 400 ms wide event windows. The acquired windows underwent different offline analysis steps (including amplitude estimation through the Optimum Filter [9], stabilization and calibration) in order to reconstruct the energy spectrum for every run and channel. All the collected data were summed up in order to obtain two overall histograms for channels coming from each tower.

Before comparing the RoI backgrounds, it was necessary to normalize the two spectra. This step allowed to account for differences in exposures due to setup geometry and analysis cut efficiencies. The 2615 keV peak of the histogram belonging to copper holder was normalized to the number of events contained in the same line of the PMMA spectrum. The computation of the normalization factor required a preliminary fit of the region around the ^{208}Tl line. Finally, the background was found by integrating the RoI region. Figure 3 shows the final result. The described procedure has been repeated for the Monte Carlo simulation. In this case, the spectra have been obtained by generating from the source position (see fig. 2) 10^7 2615 keV photons.

The overall results, reported in table I, tell that the PMMA background from experimental data is lower than the copper one. They are, indeed, different with a statistical significance of $3.8\,\sigma$. In the case of Monte Carlo backgrounds, the PMMA value is lower than the copper one by $2.1\,\sigma$. The differences between PMMA and copper backgrounds in the two cases are compatible at $1.2\,\sigma$.

We applied the same proposal to a more realistic and sensitive setup. We simulated the

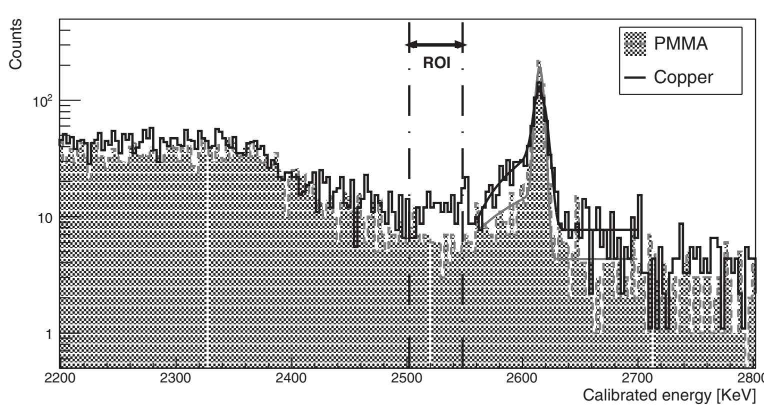

Fig. 3. – PMMA (dotted and filled histogram) and copper (solid line histogram) energy spectra around the RoI. The fit in the ^{208}Tl peak region is also drawn.

TABLE I. – *Resume of RoI backgrounds estimated for both experimental and simulated data after the energy spectra normalization.*

Data type	Holder material	RoI background [counts]
Experimental	PMMA	109 ± 10
	Copper	204 ± 23
Monte Carlo	PMMA	251 ± 16
	Copper	321 ± 30

inner structure of the CUORE experiment detector replacing the copper with PMMA. It included the 988 TeO_2 crystals, their holder components and the cable trays. The Monte Carlo generated 2615 keV γ both isotropically from a sphere around the setup and from the PMMA itself. In order to evaluate the intrinsic effect due to the material replacement, we did not consider the RoI background contribution coming from crystals themselves. It is caused by 2615 keV γ's undergoing multi-Compton scattering in a single detector. Defining the reduction factor r as the ratio between the background from the copper holder detector and the one from PMMA we obtain:

$$r = \begin{cases} 4.7^{+0.5}_{-0.6} & \text{for } \gamma\text{'s coming from outside the simulated setup,} \\ 5.0^{+0.1}_{-0.2} & \text{for } \gamma\text{'s coming from material contamination.} \end{cases}$$

4. – Conclusions

We demonstrated, with a small setup, that a light organic compound detector holder, leads to a lower γ background in the RoI of TeO_2 with respect to the same assembly made of the usual copper. The same approach is even more effective when applied to a larger setup such as the CUORE inner detector structure. The simulated γ RoI background, in this case, is ~ 5 times lower both for 2615 keV γ's generated outside the considered structure and inside the holding material as contamination. The proposal can be effective also on a broader range of $\beta\beta$ emitters, since the background obtained with the PMMA holder is lower all along the energy spectrum. The possibility to operate PMMA as scintillator would contribute also to the reduction of the α background component, along with the already-mentioned approaches. The good working properties of TeO_2 detectors with this novel holder material, including good energy resolution and faster rise and decay times, have already been verified.

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