Title
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Journal
Journal of Physics Conference Series, 2156(1)

ISSN
1742-6588

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Publication Date
2021-12-01

DOI
10.1088/1742-6596/2156/1/012228

17th International Conference on Topics in Astroparticle and Underground Physics IOP Publishing
Journal of Physics: Conference Series **2156** (2022) 012228 doi:10.1088/1742-6596/2156/1/012228

Optimization of a single module of CUPID

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Abstract. CUPID is the next generation experiment which will use scintillating cryogenic calorimeters to search for the neutrinoless double β decay. This unobserved process would shed light on the nature of the neutrino, which up to our knowledge could be a Majorana or a Dirac particle, and would give us an important hint to explain the lack of antimatter in the universe. This ambitious search needs a detector with unique characteristics such as an extremely low background level and an excellent energy resolution. CUPID is now in advanced R&D state to optimize the detector design in order to completely exploit the potentialities of scintillating cryogenic calorimeters. In the following I will describe the test performed at the LNGS (Laboratori Nazionali del Gran Sasso) of a single module of the future CUPID detector. In this contribution we present the performance obtained with a novel assembly concept, proving that it matches the requirements for CUPID.

1. Introduction

The discovery of the neutrinoless double β decay ($0\nu\beta\beta$) would establish the nature of the neutrino. Indeed, the experimental evidence of the neutrino mass model is still missing, thus in principle it could be a Dirac particle, as all the charged fermions, or a Majorana one. In the latter case, neutrino and antineutrino would coincide, giving rise to processes in which the total lepton number symmetry is violated, such as the $0\nu\beta\beta$ [1, 2]. The present sensitivity of the experiments searching for this decay ranges from 10^{24} to 10^{26} years [3, 4, 5, 6, 7] and no evidence of this decay has been found up to now. By reaching a zero background environment, the next generation experiments aim to explore the region up to at least 10^{27} years.
Cryogenic calorimeters, also called bolometers [8], are one of the most appealing technology for this search. These detectors can achieve an excellent energy resolution (about 0.2 % FWHM at few MeV) and a very high containment efficiency ($\sim$90%) since crystals work both as source and absorber. The CUORE (Cryogenic Underground Observatory for Rare Events) experiment demonstrated the possibility of building a tonne-scale detector using this technology; this is indeed a fundamental ingredient to reach the exposure needed to search for very rare events such as the $0\nu\beta\beta$. CUORE started taking data in 2017, and collected more than 1 tonne-year of exposure in stable cryogenic conditions [9]. CUORE is a fundamental milestone for the next generation experiment CUPID (CUORE Upgrade with Particle IDentification) which will be hosted in the same cryogenic facility [10]. The main upgrade of CUPID is the use of scintillating $Li_2{}^{100}MoO_4$ crystals coupled to light detectors to reject the α particles thanks to the simultaneous read-out of light and heat. Indeed, these particles represent the dominant background as demonstrated by CUORE [11]. Moreover, CUPID will search for the $0\nu\beta\beta$ decay of the isotope ^{100}Mo, whose Q-value (of about 3034 keV), laying above the natural radioactivity endpoint (at about 2615 keV), will mitigate the background contribution due to γs.
The combination of scintillating bolometers and high Q-value emitters was developed by LUCIFER [12] and LUMINEU [13]. The experience achieved by these projects resulted in 2 demonstrators which proved the CUPID working principles, CUPID-0 [14] and CUPID-Mo [15]. Many R&D measures are ongoing both at the LNGS and at the Canfranc laboratories to optimize the detector features for the CUPID experiment. The main purposes are to improve the light collection and background discrimination capabilities, to test cubic $Li_2{}^{100}MoO_4$ crystals and to analyse pile-up events, which represent one of the most important challenges to reach a background free environment in CUPID [16, 17, 18].

2. Experimental Setup

The presented prototype presents many novelties. To reduce the amount of inert material and relax the constraints on mechanical tolerances, all the detectors are on top of each others supported by gravity, while in all previous measurements these were mounted into a rigid mechanical structure. Light detectors (LD) have been re-designed to match the CUPID crystals faces; indeed, all the previous measurements used CUPID-Mo and CUPID-0 light detectors, consisting of 170 μm thick, disk-shaped Ge LD. Since CUPID will rely on cubic crystals to simplify the construction of a tightly packed array, we replaced disk-shaped light detectors with quasi-square ones.
The detector consists of 2 mini-towers made of 2 floors. Each floor hosts 2 $Li_2{}^{100}MoO_4$ cubic crystals (LMO) for a total of 8 crystals held by a copper and PTFE structure. Each crystal faces 2 light detectors on top and bottom. Light detectors consist of thin cryogenic calorimeters made of germanium (0.5 mm thick) coated with SiO (60 nm). These are placed at different distances from the crystals to test the light collection in different configurations. Both LMO and LD are equipped with a NTD-Ge thermistor to convert the temperature rise into an electric pulse. We performed 2 runs of data taking; during the first run the crystals were covered by a reflecting foil to improve the light collection, while in the second we tested bare crystals. In both runs, we

used a ^{238}U source covered by a Mylar film and faced to the crystals. In the second run only we exploited ^{232}Th strings as a source for mono-energetic γ peaks.

3. Data Analysis and Preliminary Results

The first step of the analysis was the application of a matched filter algorithm (Optimum filter) to enhance the signal-to-noise ratio suppressing the most intense noise frequencies. For the first run data, we calibrated the heat signals by exploiting the ^{238}U source and identifying the β spectrum endpoint. Instead, for the data of the second run, we performed the calibration by identifying the most intense mono-energetic peak from a ^{232}Th source. Light signals amplitude has been turned into energy calibrating each LD by using the ^{55}Fe peak at 5.9 keV.

We evaluated the performances of LDs by the RMS of the noise distribution achieved in the best working point. We didn't find any significant difference along the tower, confirming the success of the cooling along the tower and of the assembly of LDs.

The light yield (LY) has been estimated from the distribution of the light amplitude, obtained summing top and bottom LDs signals, divided by the amplitude of the corresponding heat pulse. In the case in which crystals were covered with a reflecting foil, the LYs resulted to be ∼1.2 keV/MeV and compatible between the LD-LMO spacing configurations of the first and second floors. To analyse the particle identification capabilities of the detector, we estimated the LY for α particles provided by the ^{238}U source, as done for the β/γ particle. In presence of a reflecting foil around the crystals, even taking into account the light collected by only one LD, the α particles events resulted to be completely rejected ($>$99.9 %).

In case of bare crystals, the LY is reduced on average by a factor of 2 with respect to the results obtained with the reflecting foil, as already found in the previous R&D test [16]. Nevertheless, the α particles discrimination is guaranteed in case of 2 working LDs and a bare crystals. In both cases, with and without reflecting foil, the LY is improved more than 15% with respect to the results of the 2020 Hall C R&D test in which the LD shape was circular [16].

Energy resolution of LMO has been estimated exclusively from the data of the second run. We fitted peaks from ^{208}Tl, ^{228}Ac and ^{212}Pb, present in the ^{232}Th decay chain, and extrapolated the FWHM at 3034 keV with a linear fit for each channel. Similarly, we estimated the FWHM at 3034 keV for the overall spectrum of the 8 LMO, which resulted to be compatible with the single LMO result. In both cases the percentage resolution approaches the 0.2%, which represents a promising result in view of the CUPID experiment [19].

References

[1] S. Dell'Oro, S. Marcocci, M. Viel, F. Vissani, Adv. High Energy Phys. 2016, 2162659 (2016)
[2] M. Fukugita, T. Yanagida, Phys. Lett. B 174, 45 (1986)
[3] A. Gando, et al., Phys. Rev. Lett. 117, 082503 (2016)
[4] J.B. Albert, et al., Phys. Rev. Lett. 120, 072701 (2018)
[5] C.E. Aalseth, et al., Phys. Rev. Lett. 120, 132502 (2018)
[6] C. Alduino, et al., Phys. Rev. Lett. 120, 132501 (2018)
[7] M. Agostini, et al., Phys. Rev. Lett. 120, 132503 (2018)
[8] E. Fiorini, T. Niinikoski, Nucl. Instrum. Meth. A 224, 83 (1984)
[9] D.Q.Adams et al., arXiv:2104.06906 (2021)
[10] W.R.Armstrong et al., arXiv:1907.09376 (2019)
[11] C. Alduino, et al., Eur. Phys. J. C 77, 543 (2017)
[12] D.R. Artusa, et al., Eur. Phys. J. C 76(7), 364 (2016)
[13] E. Armengaud, et al., Eur. Phys. J. C 77(11), 785 (2017)
[14] O. Azzolini, et al., Eur. Phys. J. C 79, 583 (2019)
[15] B. Schmidt et al., J. Phys. Conf. Ser. 1468, 012129 (2020)
[16] A. Armatol et al., Eur. Phys. J. C 81, 104 (2021)
[17] A. Armatol et al. JINST 16, P02037 (2021)
[18] A. Armatol et al. Phys. Rev. C 104, 015501 (2021)
[19] The CUPID Collaboration, *Paper in Preparation* (2021)