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Optimization of a single module of CUPID

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Summary. — CUPID will be the next generation experiment searching for the neutrinoless double β decay using cryogenic calorimeters. The CUORE experiment, now taking data at LNGS, demonstrated the potentiality of this technology and the feasibility of building a ton scale experiment of this kind. When CUORE will end the data taking, CUPID will take its place in the cryogenic facility. To reach a background free environment CUPID will use scintillating crystals and light detector for particle identification. In the following, the results of the R&D test at the LNGS to optimize the detector performances and the particle identification capabilities of a single module of CUPID will be described. The detector used in this test consist of 8 Li_2MoO_4 crystals and 12 light detectors. We reached to improve the results in terms of light collection by using quasi-square light detectors. Moreover, the cryogenic and noise conditions achieved in this test improved the performances in terms of energy resolution.

1. – Introduction

The double β decay, as proposed by Maria Goeppert Meyer in 1935 [1], is one of the rarest process in the universe and it has been observed in 11 nuclei in which the single β decay is energetically forbidden. The half-life of this process ranges from 10^{18} to 10^{24} years [2,3], depending on the isotope.

An alternative mode to this decay has been hypothesised by W.H. Furry in 1939 [4] and provides the emission of 2 electrons without neutrinos. The discovery of this nuclear decay, called 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. If it is a Majorana particle, neutrino and antineutrino would coincide, giving rise to processes in which the total lepton number is violated, such as the $0\nu\beta\beta$ [5]. It follows that this process can't be described by the Standard Model. Moreover it would be an hint for the explanation of the matter-antimatter asymmetry in the universe [6].

Its experimental signature is given by a mono-energetic peak at the end of the Standard Model allowed double β decay ($2\nu\beta\beta$). The present sensitivity of the experiments searching for the $0\nu\beta\beta$ ranges from 10^{24} to 10^{26} years [7-11] and no evidence of this decay has been found up to now.

The next generation experiments aim to extend their sensitivity to at least 10^{27} years. The key features of an experiment to increase the sensitivity on the $0\nu\beta\beta$ half-life are the exposure, the energy resolution and the background level. In particular, in approximation of zero background the sensitivity would scale linearly with the exposure. This is why most of the experiments searching for this rare decay are operated underground and are built with radiopure materials to mitigate cosmic rays and natural radioactivity background. Typically, shields and particle identification techniques are also needed to reach the requested background index.

One of the technologies exploited by these experiments are cryogenic calorimeters, also called bolometers [12]. They consist of crystals enriched with the isotope candidate for the $0\nu\beta\beta$ and kept at very low temperature (about 10 mK). This allows to convert the energy released by particles interacting with the crystals into thermal phonons, i.e. a temperature increase. Crystals are equipped with a cryogenic sensor to convert the temperature increase into an electric signal. The most important features of these detectors are the excellent energy resolution (about 0.2% FWHM at few MeV), achieved thanks to thermal phonons detection, the efficiency, which is very high since crystals work both as source and absorber, and a large flexibility in the choice of crystals material. Moreover, scintillating crystals can be used together with light detectors to simultaneously read-out light and heat. This technique allows to identify the kind of particle releasing energy in the crystal and eventually reject it as background.

The CUORE (Cryogenic Underground Observatory for Rare Events) experiment demonstrated the possibility of building a Ton-scale detector using this technology. It started taking data in 2017, and collected more than 1 Ton $\times$ year of exposure setting the lower limit for the ^{130}Te $0\nu\beta\beta$ half-life to 2.2×10^{25} years [13].

CUORE is a fundamental milestone for the next generation experiment CUPID (CUORE Upgrade with Particle IDentification) which will be hosted in the CUORE cryogenic facility when the actual experiment will end its data taking. The aim of CUPID is to search for $0\nu\beta\beta$ in a background free environment. To achieve this result scintillating crystals coupled to light detectors will be used to reject the background induced by α particles [14]. CUORE indeed demonstrated that this is the dominant background source, obtaining a background index of 10^{-2} counts/(keV $\times$ kg $\times$ year) [15]. By exploiting this technique, CUPID aims to bring the background index to 10^{-4} counts/(keV $\times$ kg $\times$ year) [16]. Moreover, CUPID will search for the $0\nu\beta\beta$ decay of the isotope ^{100}Mo, which present a Q-value of about 3035 keV, which is above the natural radioactivity endpoint (at about 2615 keV). This will mitigate the background contribution due to γs.

The combination of scintillating bolometers and high Q-value emitters was developed by LUCIFER [17] and LUMINEU [18], as well as by the AMoRE collaboration [21]. CUPID working principle has been proved by 2 demonstrators, CUPID-0 and CUPID-Mo. CUPID-0 used ZnSe scintillating crystals and Ge-disk bolometers as light detectors. It took data from 2017 to 2020 at the LNGS (Laboratori Nazionali del Gran Sasso), achieving the lowest background in a bolometric experiment, about 10^{-3} counts/(keV $\times$ kg $\times$ year) [19]. CUPID-Mo is taking data at the Laboratoire Souterrain de Modane since 2019, proving the excellent radiopurity and energy resolution achieved with Li_2MoO_4 crystals [20], which have been chosen for CUPID. Many R&D tests 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_2MoO_4 crystals and to analyse pile-up events, which represent one of the most important challenges to reach a background free environment in CUPID [22-24]. In the following I will describe the test made in the Hall C of LNGS to optimize the assembly and the light detectors of a CUPID single module.

2. – Experimental setup

The detector consists of 2 mini-towers made of 2 floors. Each floor hosts 2 Li_2MoO_4 cubic crystals (LMO) for a total of 8 crystals held by a copper and PTFE structure. Each crystal faces 2 light detectors (LD) on top and bottom. Light detectors consist of a thin cryogenic calorimeters made of germanium coated with SiO. The quasi-square shape of LDs, tested in this run for the first time, allows to fully cover the crystals faces. Both LMO and LD are equipped with a NTD-Ge thermistor to convert the temperature rise into an electric pulse.

We tested 2 possible configurations of LDs for the future CUPID experiment; in the first floor, LDs are spaced 0.5 and 4 mm from the crystal, while in the second the bottom LDs are spaced 0.5 mm and the top LD is leaned on top of the crystal (gravity assisted LD).

We performed 2 runs of data taking. During the first run the crystals were covered by a reflecting foil to improve the light collection. An intense ^{238}U source covered by a Mylar film was placed on the reflecting foil, facing the crystal. During the second run the reflecting foil has been removed to test the light collection with bare crystals. So a new ^{238}U source has been placed on the detector structure and a ^{232}Th string has been used for β/γ calibration.

3. – Data analysis

The voltage signals were amplified and filtered with a Bessel filter and a derivative trigger was applied to the data to identify thermal pulses. Moreover a random trigger was set every 60 s to sample the noise waveforms.

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. To perform Particle Identification, any LD waveform coincident with a pulse of the corresponding LMO is acquired and flagged as side pulse. In order to improve the estimate of the side pulses amplitude, we exploited the fixed time delay between light and heat pulses due to the electronics jitter. This allows to remove some non-linearities introduced by the optimum filter at low energies, while, it does not affect the light signals amplitude in the region of interest [25].

For the first run, we calibrated the heat signals by exploiting the ^{238}U source, which is placed inside the detector close to each LMO. For the second run, we performed the calibration by using ^{232}Th strings. We identified and fitted the most intense monoenergetic peaks in the spectrum and we used a second order polynomial function crossing the origin as calibration curve. Light signals amplitude has been turned into energy calibrating each LD by using the ^{55}Fe peak at 5.9 keV.

We evaluated the performance of the heat channel exclusively from the second run data. Indeed, in this case it was possible to improve detector energy resolution by correcting the temperature dependence of the pulses amplitude.

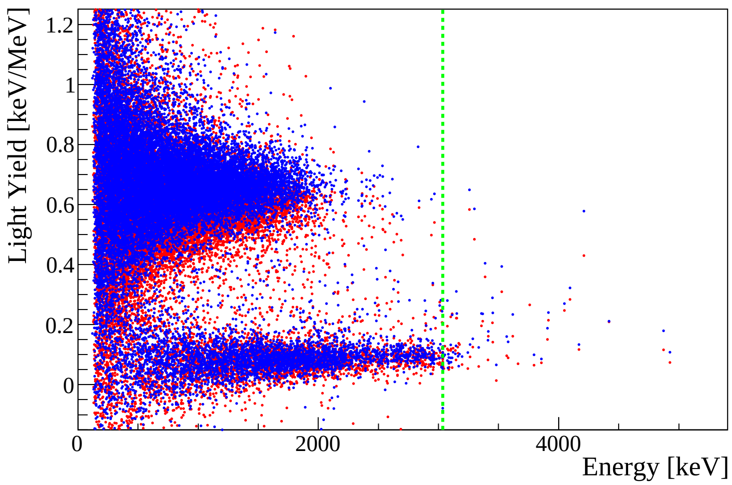

Fig. 1. – Light Yield as a function of the energy of a single LMO, red points are from the LD on top, spaced 4mm, while blue from the bottom LD, spaced 0.5 mm. Data are from the first run in which crystal was covered by a reflecting foil. The green line indicates the ^{100}Mo double β decay Q-value.

4. – Results

One of the purpose of this test was to analyse the LDs performances. The baseline RMS, estimated from a Gaussian fit of noise events, resulted to be between 40 and 70 eV for most of the LDs. We didn't find any significant difference in the LD performances along the 3 floors of the tower. This confirms the success of the cooling along the tower and the uniformity of the results among the different LDs assembly.

The main purpose of this run was to evaluate the light collection obtained with quasi-square LDs and compare the results obtained with different spacing from the crystals. We estimate the light yield (LY) as the mean of the distribution obtained after summing the light amplitude, converted into energy, of top and bottom LDs and dividing it by the energy estimated from the heat pulse. Indeed, only a fraction the energy is converted into scintillation and detected by the light detectors. Events are selected with an energy higher than 1.2 MeV.

In the following the results of the first run, in which crystals were covered with a reflecting foil, will be described. The LYs resulted to be higher than 1.2 keV/MeV and compatible between the 2 configurations, thus we can conclude that LDs are collecting the same amount of photons. Moreover, the photon collection is saturated since the LY of the single LDs compensate each other. This leads to the conclusion that a closer LD collect more light, subtracting photons from the other LD.

To analyse the discrimination capabilities of the detector, we estimated the LY for α particles provided by the ^{238}U source, by applying the same cuts as for the case of β/γ particles. Then, in order to quantify the particle identification capabilities, we defined a Discrimination Power (DP):

$$DP \equiv \frac{\left|LY_{\beta/\gamma} - LY_{\alpha}\right|}{\sqrt{\sigma^2_{\beta/\gamma} + \sigma^2_{\alpha}}}. \quad (1)$$

We found a DP higher than 5 for any LD, which guarantees a complete rejection of α particles (>99.9 %). Figure 1 shows the LY as a function of the energy for top LD (in red) spaced 4 mm, and bottom LD (in blue) spaced 0.5 mm, in case of crystal covered with reflecting foil. The 2 populations corresponds to β/γ (at higher LY) and α particles.

We performed the same analysis on the data taken during the second run, in which the reflecting foil has been removed. In this case the LY in the 2 configuration is not compatible, thus the light collection saturation is lost in case of bare crystals. The effect of compensation between the 2 single LDs is not present anymore. With respect to the results obtained with the reflecting foil on average the LY is reduced by a factor of 2, as already found in the previous R&D test [22]. The α particles discrimination is guaranteed in case of 2 working LDs and a bare crystals as the DP is always higher than 5. The results on the LY are improved of about 15-20 % with respect to the results obtained during the 2020 Hall C R&D test in which the LD shape was circular [22].

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