IL NUOVO CIMENTO **46 C** (2023) 118
DOI 10.1393/ncc/i2023-23118-6

COMMUNICATIONS: SIF Congress 2022

Study on the homogeneity of large-size LYSO:Ce crystals for the HEPD-02 electromagnetic calorimeter

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received 30 January 2023

Summary. — LYSO:Ce crystals are known for their high light output, good energy resolution, compact size and radiation hardness, making them ideal for high-energy physics experiments and medical imaging. These properties also make LYSO:Ce crystals suitable for space-based astroparticle physics experiments. Therefore, the LIMADOU collaboration selected this material to develop a compact electromagnetic calorimeter with 9 LYSO:Ce crystals of $5 \times 5 \times 4$ cm^3 for the High Energy Physics Detector HEPD-01 mounted on the CSES satellite about 5 five years ago. Now, a second payload HEPD-02 is being constructed with 6 LYSO:Ce samples of $15 \times 5 \times 2.5$ cm^3 fabricated by Filar OptoMaterials, enabling the development of a calorimeter with LYSO:Ce crystals two times larger in volume than the previous one. Since the growing process of crystals of this size requires new techniques for the company, an extensive experimental campaign is necessary to determine the properties of the samples. To this end, the INFN-TIFPA group, involved in the LIMADOU collaboration, has conducted a thorough study of 16 crystals. This paper summarises the main results of this characterization.

1. – Introduction

Time-resolved measurements of the differential energy distribution of (relatively low-energy) charged particles in space are interesting to study Space Weather and the possible coupling of the Lithosphere, Atmosphere, Ionosphere and Magnetosphere (LAIM). In particular, some experimental evidence [1] and some theoretical models [2] involve the correlation between seismic activity, ionospheric disturbances and electromagnetic emissions in the Earth's atmosphere. The China Seismo-Electromagnetic Satellite CSES goal is to gain new insights into the relationship between seismic activity and the Earth's

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atmosphere/ionosphere/magnetosphere. For these studies, the CSES mission uses a combination of instruments to measure the density and distribution of charged particles in the ionosphere and electromagnetic emissions. The first satellite, CSES-01, was successfully launched in 2018, and the second one is being prepared for launch in early 2024. The Italian LIMADOU collaboration developed the High Energy Particle Detector (HEPD) payload for the first satellite (HEPD-01, [3]) and the gained experience was the starting point for the construction of HEPD-02, which is now ready for launch. HEPD-02 is a payload that will be mounted on the CSES-02 satellite and will measure electrons between 3 and 100 MeV and protons between 30 and 200 MeV. The main differences between the first and the second payload are the tracker and the LYSO:Ce calorimeter size. In particular, the tracker is made of Monolithic Active Pixel Sensors (MAPS), which are ALTAI chips, representing the first tracker in space that mounts this technology [4]. Additionally, large-size LYSO:Ce crystals improve energy collection and lower the number of photodetectors needed. In the following sections, a summary of the characterisation of these large-size LYSO:Ce crystals is presented.

2. – LYSO:Ce crystals

LYSO:Ce was originally discovered by C.L. Melcher and J.S. Schweitzer when they were looking for a high-quality scintillator material for PET detectors [5]. LYSO:Ce has a high light yield ($\sim$30000 photons/MeV), a fast decay time ($\sim$40 ns), excellent energy resolution ($\sim$8% at 662 keV), and a high density ($\sim 7.3\,\mathrm{g/cm^3}$) [6]. Both ground and space experiments such as CMS at LHC and HERD have chosen LYSO:Ce for calorimeter detectors. CMS LYSO:Ce crystal dimensions are $3 \times 3 \times 57\,\mathrm{mm^3}$ [7], the HERD ones are $30\times30\times30\,\mathrm{mm^3}$ [8] and the HEPD-01 ones are $50\times50\times40\,\mathrm{mm^3}$ [3]. The chemical composition of LYSO:Ce is $\mathrm{Lu_{2(1-x)}Y_{2x}SiO_5 : Ce}$; it contains natural Lu, which has about 2.6% of the radioactive ^{176}Lu isotope. Therefore, this material is affected by an intrinsic radioactive background. The ^{176}Lu decays by β emission with a half-life of $3.76{\cdot}10^{10}$ years. The average and maximum β energies are 182 keV and 593 keV, respectively. However, the decay also produces excited states of the daughter ^{176}Hf. The excited states produce three γ lines with 88, 202 and 307 keV energies. This internal contamination produces a complex and continuous spectrum through the simultaneous emission of the β rays and the absorbed γ rays, which provide an important background for the detection of sub- MeV γ rays in space. In HEPD-02, two layers of three crystals ($15\times5\times2.5\,\mathrm{cm^3}$) produced by Filar OptoMaterials [9] are placed orthogonally, corresponding to a thickness of $\sim 4.4\mathrm{X_0}$. The crystals are wrapped with aluminised Mylar to reduce optical crosstalk and augment photon collection. Two Hamamatsu R9880-210 PMTs collect the light at the edges of the long side of the crystal through a 3 mm thick EJ-560 optical coupling.

3. – Light output characterization

To measure the light output of the crystals as a function of the impact point of the particles, we used a pixel-based MAPS tracking system, as developed for HEPD-02, to track atmospheric muons traversing the LYSO:Ce samples. We then logically segmented the detector surface into 75 bins of $1 \times 1\,\mathrm{cm^2}$ by selecting the impact location of the muons. For each bin, we measured the most probable value (MPV) of the signal

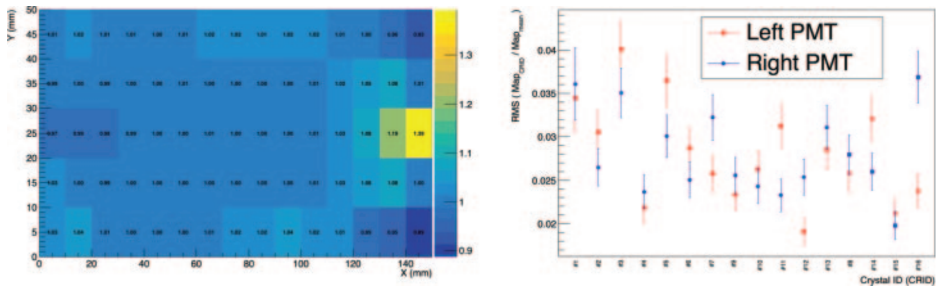

Fig. 1. – Left side: measured signal MPV variation map (with cosmic muons) taken with a PMT at $x = 150$ and $y = 25$ mm (MPVs are normalized to that measured in the centre). This map represents the mean one among the 16 crystals. Right side: RMS of the ratio bin to bin (75 values) between the map of each crystal and the mean one. Crystal ID (CRID) from 1 to 6 are mounted in the Flight Model (FM), 7 to 12 in the Qualification Model (QM) and the rest are spares.

amplitude distribution to calibrate the detector response. By plotting the MPVs against the position of the bin, we obtained an MPV map similar to that shown in fig. 1 (left side). The map is normalised to the signal MPV measured in the centre of the crystal. The measured variation of the MPV values along the map is mainly due to the expected position-dependent light collection efficiency. In particular, the proximity of the incidence point to the sensitive region of the PMT (at $x = 150$ and $y = 25$ mm bin, in front of the PMT) provides a $\sim$40% larger signal MPV. Such a map was obtained for each crystal, allowing us to calculate the mean among the 16 samples (fig. 1, left). Considering the RMS of the ratio between the individual maps and the mean one, it is possible to investigate the subdominant effect due to the spatial non-uniformity of the scintillation light yield in each of the 16 different crystals (fig. 1, right). The correlation between the two independent RMS pair evaluations (using the left and right sides PMT, red/circle and blue/square dots in fig. 1) indicates the discovery of a typical spatial non-uniformity of the order of 3% along these crystals. This result shows that there are no significant optical differences between the crystals. Furthermore, beam tests were performed on the HEPD-02 LYSO:Ce crystals. Figure 2 shows the comparison between the MPV signal measurements and the Geant4 simulation of a beam test with protons in the range of 60 to 230 MeV performed at the Trento Proton Therapy Centre [10]. In the left side of fig. 2, the LYSO:Ce #1 crystal was placed so that the beam hit (or passed through) 2.5 cm of LYSO:Ce material, while on the right side, the case of 5 cm LYSO:Ce material is shown, with the crystal rotated 90°. With these settings, the protons start to have enough energy to cross the crystal at about 120 MeV (for the 2.5 cm side) and 180 MeV (for the 5 cm side). The reduction in energy deposition in the crystal for relatively high-energy (crossing) protons is due to the well-known behaviour of specific energy loss for non-relativistic charged particles. A remarkable phenomenon is that the measured signal MPV for protons stopped in the crystal is much smaller than the simulated one. This expected effect is due to Birks' scintillation quenching, which was intentionally not included in the simulation. This quenching phenomenon can be described for the LYSO:Ce material by the (modified) Birks-Onsager effect [8]. A detailed analysis of the LYSO:Ce scintillation quenching parameters for HEPD-02 crystals is underway.

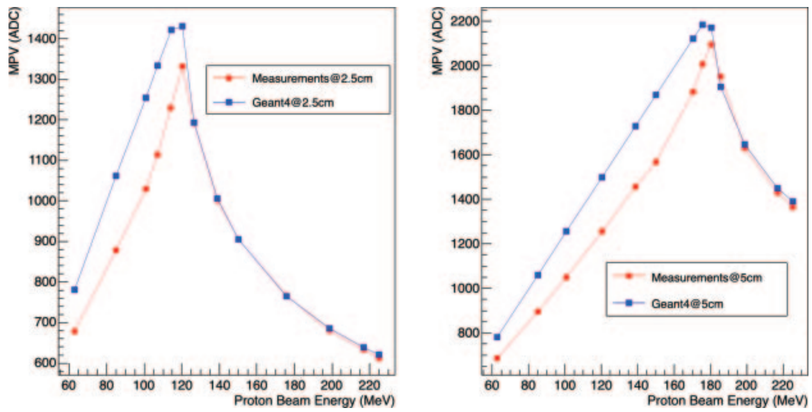

Fig. 2. – Test beam results with protons. In the y-axis, we report the MPV of the signal produced by about 10000 protons hitting the detector (in ADC) at each starting energy (shown in the x-axis). On the left side, the setup was mounted so that the protons see 2.5 cm of LYSO:Ce, and start to cross it at about 120 MeV; on the right side, the protons see 5 cm of LYSO:Ce, and start to cross it at about 180 MeV. ADC values of the simulation are obtained with a scaling factor of ~10 ADC/MeV obtained by a calibration measurement with radioactive sources. The discrepancy between the data and the simulation for strongly ionising stopped protons can be attributed to Birks' quenching (which was intentionally not considered in this simulation). The error bars of the measurements lie within the mark.

4. – Conclusions

The large-size LYSO:Ce scintillators fabricated by Filar OptoMaterials for HEPD-02 have been studied in long experimental campaigns, including cosmic muon measurements, test beams and Geant4 simulations. The 16 tested crystals show a uniform response, and no large inhomogeneities in the light yield have been found within the samples. A signature of Birks' scintillation quenching effects was observed during the beam tests. A detailed analysis will be carried out to allow for the direct measurement of the Birks'-Onsager parameters.

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