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Exploring the Efficiency of HEPD-02 LYSO:Ce Scintillators in the CSES-02 Satellite Mission for Detecting Gamma-Ray Bursts

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The CSES-02 satellite mission seeks to expand our knowledge of the interconnection between the Earth's lithosphere, atmosphere, ionosphere, and magnetosphere. Various instruments will measure the electromagnetic environment around the satellite, which will fly in a Sun-synchronous orbit at approximately 500 km from the ground. The HEPD-02 payload, developed by the Italian Limadou collaboration, is a fundamental component of the mission. It measures the flux of protons (30 to 200 MeV) and electrons (3 to 100 MeV) trapped in the Van Allen Belts, representing an indispensable instrument for studying the ionosphere and the magnetosphere. The HEPD-02 payload mounts LYSO:Ce scintillating crystals to measure the energy of impinging particles. Limadou chose LYSO:Ce due to its fast decay time (40ns), high density (7.1 g/cm3) and high light yield (about 30000 ph/MeV). The module made of LYSO crystals and its relative acquisition system will be sensitive to Gamma-Ray Bursts of energy larger than 2 MeV, a range currently covered by experiments like HXMT, Fermi, and INTEGRAL. With an optimal energy resolution, HEPD-02 will contribute to expanding the coverage of the sky for the detection and study of GRBs. We will report on the sensitivity of HEPD-02 to short and long GRBs, obtained with an Elekta medical LINAC model SL15.

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PoS(ICRC2023)758

1. Introduction

The China Seismo-Electromagnetic Satellite (CSES), participated in by the Italian collaboration Limadou, aims to investigate the complex interconnection between the Earth's lithosphere, atmosphere, ionosphere, and magnetosphere. Launched in 2018, the first CSES satellite is designed to explore and understand the electromagnetic phenomena associated with seismic activities and other geophysical processes. The High-Energy Particle Detector-02 (HEPD-02) is a payload developed by the Limadou collaboration for the second CSES space mission. HEPD-02 serves as a fundamental instrument for studying the ionosphere and magnetosphere by measuring the flux of protons (30 to 200 MeV) and electrons (3 to 100 MeV) trapped in the Van Allen Belts at about 500 km from the ground in a Sun-synchronous orbit. In recent times, the CSES mission has yielded significant results, extending beyond charged particle observations to include the detection of photons in space. Notably, the instruments of the first CSES mission achieved a remarkable milestone by successfully detecting an intense Gamma Ray Burst (GRB). GRB221009A was measured with exceptional precision, even though the mission lacked a dedicated acquisition system or specific design for such GRB measurements [1]. This achievement showcases the capability and versatility of the CSES instruments in exploring and uncovering various astrophysical phenomena. Furthermore, events like GW170817/GRB170817A [2] proved how important is to count on many independent experiments to make good observational science.

SCINTILLATOR PROPERTY	LYSO	BGO
Density (g/cm^3)	7.1	7.1
Attenuation length for 511 keV (cm)	1.2	1.0
Decay time (ns)	36	300
Energy resolution @ 662 keV	8.0	12.0
Light output, photons per keV	33	9
Average temperature coefficient 25 to 50 ^{o}C (%/^{o}C)	-0.28	-1.2

Table 1: Comparison of LYSO:Ce and BGO crystals given by Saint-Gobain.

In this study, we focus on exploring the distinct advantages of utilizing LYSO:Ce (Lutetium Yttrium Oxyorthosilicate doped with Cerium) as the energy detection material for detecting Gamma Ray Bursts (GRBs). The HEPD-01/02 instruments have adopted LYSO:Ce crystals due to several key properties that render them highly suitable for GRB detection, significantly enhancing the overall performance of these instruments. A comparison between LYSO:Ce and the standard reference material, high-performance BGO (Bismuth Germanate), used for GRB detection in FERMI [5], is presented in Table 1. Notably, LYSO:Ce exhibits comparable density to BGO but showcases advantages such as faster decay time, higher light output, superior energy resolution, and a lower temperature coefficient. However, the utilization of LYSO:Ce is not without challenges, as it exhibits high intrinsic radioactivity primarily attributed to the presence of the radioactive isotope ^{176}Lu, emitting radiation at approximately 40 Bq/g. Despite this drawback, the Limadou collaboration has selected LYSO:Ce as the material of choice for the energetic calorimeter in the HEPD-02 instrument, highlighting its superior performance characteristics for GRB detection over the standard BGO. In

PoS(ICRC2023)758

the subsequent sections, we will provide a detailed analysis of the crucial aspects of LYSO:Ce that significantly influence its ability to detect GRBs.

2. Effective area of HEPD-02 for GRBs

HEPD-02 is designed to perform precise reconstruction of energy and direction of particles, as well as to identify their type. This is achieved through the utilization of various key components, including a silicon tracker based on Monolithic Active Pixel Sensors (MAPS) ALTAI chips [4], EJ-200 plastic scintillators, and LYSO:Ce crystals, as illustrated in Fig. 1, left. The trigger system is comprised of two layers of EJ-200 plastic scintillators, positioned above and below the silicon tracker, with thicknesses of 2mm and 8mm, respectively. The range calorimeter consists of 12 layers of EJ-200 plastic scintillators, each with a thickness of 10 mm. For the energy calorimeter, two layers of 3 LYSO:Ce scintillators are employed, each having dimensions of 150x50x25 mm^3. Additionally, five EJ-200 scintillators with a thickness of 8 mm are positioned to cover laterally and under the system, serving as veto triggers (not shown in the image). Both the plastic scintillators and LYSO:Ce crystals are read by two Hamamatsu R9880-210 PMTs each. The choice of large-size LYSO:Ce crystals was considered optimal, striking a balance between minimizing the number of photodetectors required and achieving a high level of granularity. The energy detector material budget amounts to $4X_0$, and the cross-sectional area of the crystals exceeds the Molière radius (approximately 20 mm) in each dimension.

In this study, we employed a Monte Carlo simulation based on Geant4 [6] to assess the effective area for photons that reach the range (plastic) or energy (LYSO) calorimeter, while considering a combination of the plastic scintillators as vetoes (see eq. (1), (2).). The main objective of the simulation was to analyze and understand the individual contributions of the range calorimeter and LYSO:Ce crystals, shedding light on their respective responses in the detection process (see Fig. 1, right).

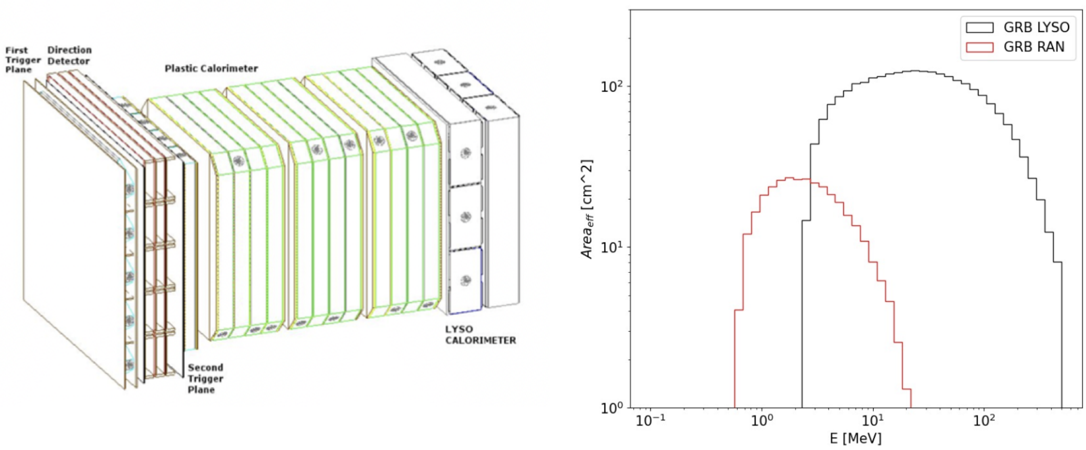

Figure 1: Left: the design sketch of HEPD-02. The plastic calorimeter and trigger planes are EJ-200 material. The direction detector comprises ALTAI chips [4]. Right: the on-axis effective area of HEPD-02 for photons is presented, considering two distinct GRB masks (see eq. (1) and (2)).

PoS(ICRC2023)758

The thresholds for the EJ-200 scintillators and LYSO:Ce crystals were carefully chosen for the HEPD-02 instrument. The EJ-200 scintillators have a threshold set at 1/4 of the Minimum Ionizing Particle (MIP) energy release, which corresponds to around 500 keV. On the other hand, the LYSO:Ce crystals have a threshold set at 1/10 of MIP, approximately 2 MeV. This particular choice was made to prevent triggering due to the intrinsic radioactivity of LYSO:Ce (further details will be discussed in the subsequent sections). In terms of the measurable photon energies, the highest energy photons that can be detected by the two masks are approximately 20 MeV for the range (RAN) calorimeter and 500 MeV for LYSO. Above these energies, the acquisition is vetoed. Focusing on the region where the effective area exceeds 10 cm^2, the energy range covered by HEPD-02 for GRBs spans from around 800 keV to 200 MeV. Notably, the effective area reaches a plateau value of about 150 cm^2 between 5 and 50 MeV, which corresponds to nearly half of the LYSO:Ce covered area (225 cm^2), showing the excellent detection capability of the LYSO calorimeter. In the upcoming sections, the motivations behind the 2 MeV energy threshold for LYSO:Ce will be elucidated through a series of specific measurements conducted on the samples mounted in the Flight Model (FM).

3. Estimation of the LYSO:Ce intrinsic radioactivity

The HEPD-02 instrument utilizes scintillating crystals composed of Lutetium Yttrium Oxy-orthosilicate doped with Cerium (LYSO:Ce) as its energy detection material. However, this high-performance crystal comes with the trade-off of having high intrinsic radioactivity, primarily due to the presence of the radioactive isotope ^{176}Lu, which emits radiation at a typical rate of about 40 Bq/g. This elevated radioactivity is the main reason why this crystal has not been widely used in space applications until now.

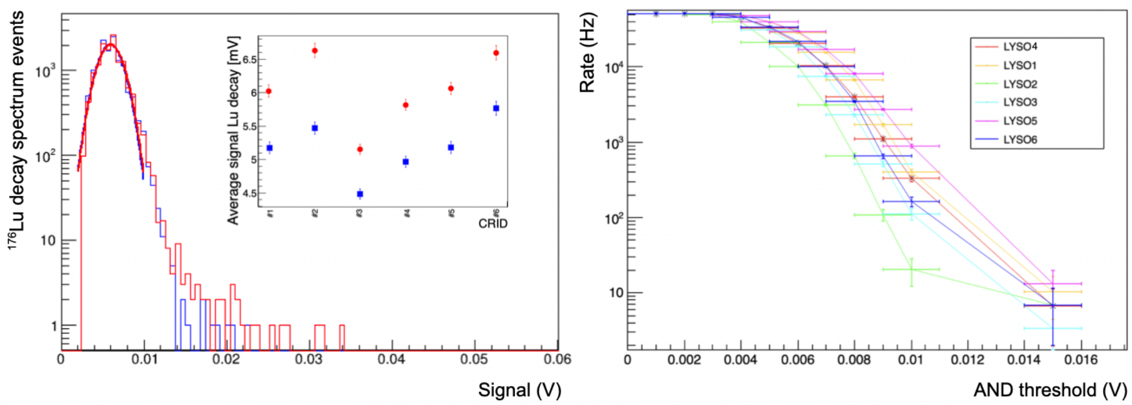

Figure 2: Left: The first PMT of the LYSO bar is marked in red/circle, and the second one in blue/square. The average signal from intrinsic radioactivity is evaluated using a Gaussian fit on the signal spectrum. ^{176}Lu undergoes β^- decay, emitting an electron with an average and maximum energy of 182 and 593 keV, respectively, and has a half-life of approximately 10^9 years. Additionally, three prompt gamma rays with energies of 88, 202, and 307 keV are emitted during the decay process. The difference between the red (first PMTs) and blue (second PMTs) in the plot is due to a small difference in the PMT gain that was not equalized. Right: The measured trigger rate is shown by varying the threshold of the two PMTs read in logic AND.

PoS(ICRC2023)758

To quantify the spectrum produced in the crystals by ^{176}Lu, we connected the two Hamamatsu R9880-210 PMTs coupled with the crystal to a TELEDYNE LeCroy HDO910 oscilloscope using a logic AND with a low threshold (approximately 300 keV). The typical intrinsic radioactivity spectrum, as depicted in Fig. 2 (left), was obtained for Crystal ID CRID = 1. The average Most Probable Value (MPV) of the spectrum for all six crystals is approximately 5-6 mV (equivalent to about 700-800 keV). Based on this measurement, we assessed the trigger rate attributed to ^{176}Lu by varying the threshold value for each crystal, as shown in Fig. 2 (right). Placing the threshold at the end of the ^{176}Lu spectrum effectively minimizes false triggers that could be triggered by the radioactive emissions from the crystal material. Ultimately, we selected a threshold corresponding to 15 mV (approximately 2 MeV), resulting in a trigger rate of about 10 Hz. Since the Minimum Ionizing Particle (MIP) energy release is approximately 25 MeV, we chose to set the threshold at 1/10 MIP, close to 2 MeV. This decision establishes the minimum detectable gamma energy value in the LYSO:Ce crystals to be 2 MeV. This result is also essential for determining the threshold of the trigger mask in the GRB acquisition algorithm.

4. Dedicated trigger masks for GRBs and acquisition algorithm

The detection of a Gamma Ray Burst (GRB) by the energy calorimeter is characterized by a rapid increase in the counts per second recorded by the PMTs. To accurately capture the shape of the GRB in the time domain, a specific algorithm with optimal timing performance is integrated into the Data Acquisition (DAQ) system of HEPD-02. To detect GRBs, two trigger masks are implemented in conjunction with the masks dedicated to detecting charged particles. The GRB detection is defined as follows:

$$GRB_{LYSO} = \mathrm{OR}(EN1, EN2)\&\neg\mathrm{OR}(RAN12, LAT, BOT) \quad (1)$$

$$GRB_{RAN} = \mathrm{OR}(RAN5, RAN6, RAN7, RAN8)\&\neg\mathrm{OR}(RAN4, RAN9, LAT) \quad (2)$$

The subscripts refer to the GRB detection triggered by the LYSO and the range calorimeter (RAN) components, respectively. The symbol OR represents the logical "OR" operation, while $\neg$ represents the logical negation (NOT) operation. The terms $EN1$ and $EN2$ represent the energy triggers from the first and second layers of LYSO:Ce scintillators, respectively. On the other hand, RAN denotes the range calorimeter triggers, where $RAN1$ represents the first scintillator from the top, and $RAN12$ corresponds to the scintillator closest to the first layer of LYSO:Ce. The scintillators placed in the $\neg$OR logic serve as vetoes to avoid triggering on charged particles. In each scintillator, the logic AND operation is performed between the signals from the two PMTs. The arrangement of the scintillators in the trigger masks allows HEPD-02 to efficiently detect and analyze Gamma Ray Burst events, while also excluding triggers caused by charged particles through the use of appropriate vetoes.

The GRB detection algorithm is activated only when HEPD-02 operates outside the South Atlantic Anomaly (SAA) and the poles, as these regions experience a high false trigger event rate. As illustrated in Fig. 3, the algorithm calculates the Moving Average Value of the PMT event count (MAV) and the Mean Absolute Difference (MAD) at intervals of 5 ms. The selection of

PoS(ICRC2023)758

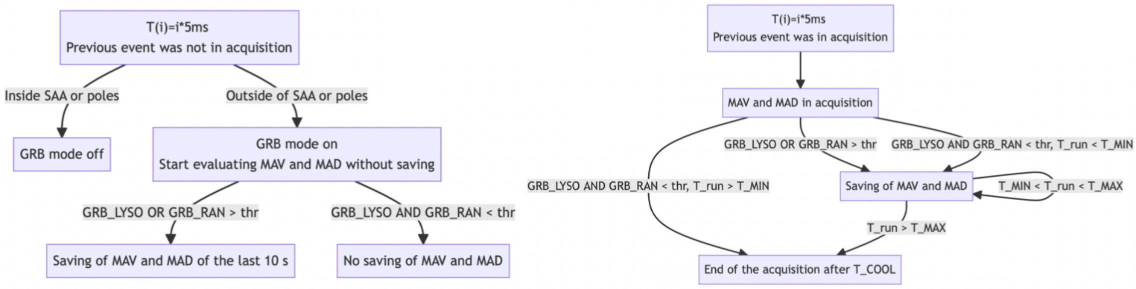

Figure 3: Algorithm scheme of the acquisition of a Gamma-Ray Burst (GRB). Left: The acquisition scheme is depicted for cases where the system is not in acquisition in the previous event. Right: The acquisition scheme is illustrated for cases where the system is in acquisition during the previous event.

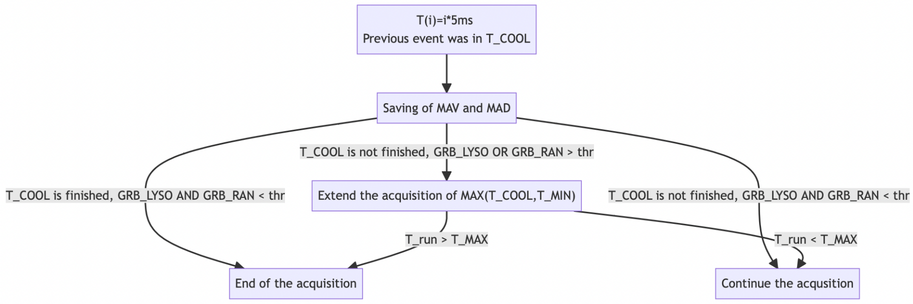

Figure 4: Algorithm scheme for the acquisition of a Gamma-Ray Burst (GRB) when the previous event occurred during the T_{COOL} period.

these estimators is motivated by their ability to consider the background count rate (i.e., noise, LYSO intrinsic radioactivity, and charged particles) with computational efficiency. The algorithm is enabled if either of the two masks is triggered, which occurs when $Signal > MAV + k \times MAD$, with k being a parameter specific to each scintillator type (RAN or LYSO) and the time interval considered for estimating MAV and MAD. k will be tuned during the commissioning. Two separate buffers store MAV and MAD for the two masks, and these buffers are recorded even if only one of the masks is triggered. After the GRB event, when the trigger signal returns to its baseline level, the Data Acquisition (DAQ) system imposes a cooling time T_{cool} before ending the acquisition (see Fig. 4). The minimum acquisition time is set to T_{min} = 2 s, while the maximum acquisition time is set to T_{max} = 600 s. If the trigger signal returns to its baseline and then rises again before T_{cool} elapses, the acquisition is extended by $max(T_{cool}, T_{min})$ seconds. This process can be repeated until T_{max} is reached, which then terminates the acquisition. The default parameter settings are T_{cool} = 90 s, T_{min} = 2 s, and T_{max} = 600 s.

4.1 GRB detection performance tests with a medical LINAC

After calibrating the LYSO:Ce samples before assembling HEPD-02, we conducted a series of test beam measurements to evaluate the performance of the GRB detecting algorithm. For these tests, the Limadou collaboration opted to use a medical linac photon beam at the Trento S. Chiara Hospital to assess HEPD-02 response to both short and long photon beams. The Trento

PoS(ICRC2023)758

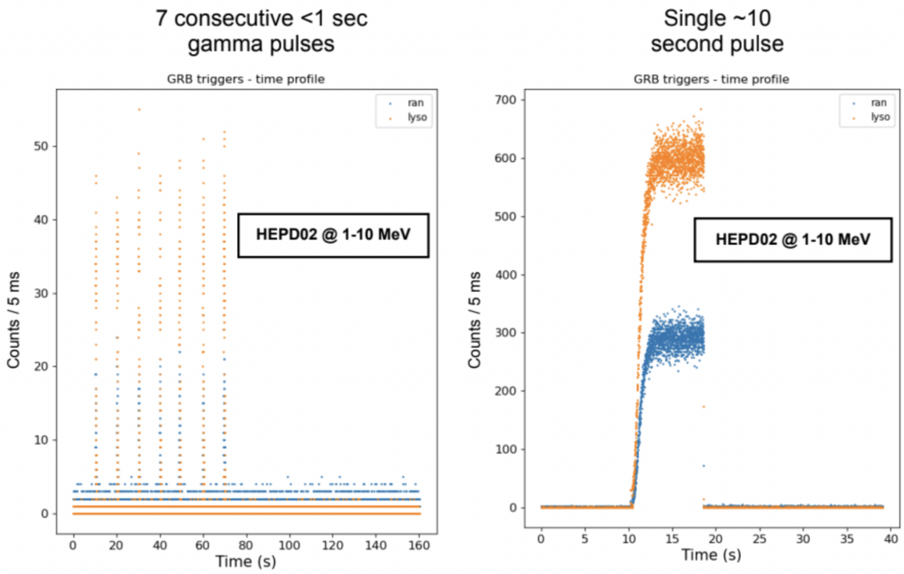

Figure 5: HEPD-02 conducted measurements of seven short gamma pulses and a long pulse generated by a linac Elekta SL15 operating at 10 MV. The blue points represent the counts obtained with the GRB_{RAN} mask, while the orange points correspond to the counts registered with the GRB_{LYSO} mask.

S. Chiara Hospital possesses an older Elekta medical linac model SL15 [7], capable of producing electrons with energies of 6, 9, and 12 MeV, as well as photons generated through bremsstrahlung emission by electrons at acceleration potentials of 4, 6, and 10 MV. To ensure stability and minimize pileup effects, an appropriate current was chosen for the tests. HEPD-02 was operated in photon mode with a 10 MV acceleration potential, as it exhibited better stability at low currents. During the tests, the beam was focused using a beam stopper system to achieve a spot size of 1x1 cm^2, and the HEPD-02 top window was positioned approximately 5 cm from the beam exit. A set of different measurements was collected by varying the algorithm parameters and the duration of the beam. The beam duration was chosen to simulate both short and long pulses, ranging from 1 second to about 60 seconds. The timing performance of the DAQ algorithm was evaluated, and the results are presented in Fig. 5, which demonstrates the successful recording of 7 consecutive gamma pulses shorter than 1 second and 1 long pulse lasting about 10 seconds by HEPD-02. To further investigate the instrument response to photon events, a Monte Carlo simulation is currently underway to compare the measured energy release by photons in the LYSO:Ce crystals. These simulation results will be presented in future works, providing valuable insights into the detector's performance.

5. Conclusions

The presented work involved the experimental characterization of the LYSO:Ce intrinsic radioactive spectrum, which was utilized to determine the appropriate energy threshold in the trigger mask, effectively avoiding false triggers. This threshold was determined to be 2 MeV, ensuring a contribution of approximately 10 Hz. Subsequently, the effective area was calculated using this

PoS(ICRC2023)758

energy threshold value, equivalent to 1/10 of MIP. The main components of the GRB detection algorithm and the trigger mask were comprehensively described. Experimental tests of the GRB algorithm were conducted using an SL15 Elekta linac with 10 MV photons of varying durations. The algorithm demonstrated excellent performance during the tests, successfully detecting a set of 7 short pulses (<1s) and a long pulse lasting about 10 seconds. An extensive Monte Carlo campaign is currently in progress to reconstruct the energy release in the LYSO:Ce crystals and the results will be presented in a dedicated future publication. As a result of these successful tests and developments, the HEPD-02 payload is now thoroughly validated and ready for launch from the Gobi Desert, scheduled for the beginning of 2024.

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PoS(ICRC2023)758