

Simulation of GRIS spectrometer response to the solar gamma-ray flare of 23 July 2002

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Abstract. GRIS is a prospective experiment designed to measure hard X-rays and γ -rays of solar flares in the energy range from 50 keV to 200 MeV as well as solar neutrons > 30 MeV. This study considers results of GEANT 4 simulation of GRIS detectors response to cosmic background radiation and to the solar flare SOL2002-07-23 (X4.8). It is shown that the GRIS spectrometers have enough sensitivity and energy resolution to measure redshifts of some narrow γ -rays in flare spectra, that the low energy thresholds of the detectors can be lowered considerably without a risk of counting rate saturation during high magnitude flares and that at a choice between $\text{LaBr}_3(\text{Ce})$ and CeBr_3 the second one is a preferable scintillator for a hard X-ray and γ -ray spectrometer of solar flares.

1. Introduction

A hard X-ray and γ -ray spectrum of a high magnitude solar flare carries information about particles acceleration and propagation occurred in the solar atmosphere due to releasing of magnetic energy. This spectrum has the complicated structure which appears as a result of the interactions of accelerated particles with ambient plasma [1]. The collisions of relativistic electrons with thermal ions produce bremsstrahlung radiation with a power low spectrum in the energy range over a few tens of keV. The nuclei excited by protons and α -particles accelerated up to 10-30 MeV/nucleon generate the narrow nuclear lines in 0.3-8 MeV energy range. More energetic protons and α -particles can produce neutrons that may be captured by hydrogen nuclei with emitting of 2.22 MeV photons or escape from the Sun and reach the Earth (in case of $E_n \geq 20$ -30 MeV). The most energetic protons (> 300 MeV) generate charged and neutral pions. The decays of the last ones form in a flare spectrum the broad peak with the maximum of about 70 MeV. π^+ decays give positrons that produce the annihilation line of 511 keV.

GRIS (Gamma and Roentgen radiation of the Sun) is a prospective experiment designed to measure hard X-rays and γ -rays of solar flares with the energy range from 50 keV to 200 MeV. It's also designed for the registration of direct solar neutrons. The apparatus will be mounted at the oriented platform outside the Russian Orbital Segment of the International Space Station. The instrument includes two detector heads: a low energy spectrometer (LES) based on a fast scintillator with relatively high energy resolution 3.5–4.5% at 662 keV ($\text{LaBr}_3(\text{Ce})$ or CeBr_3) has the size of $\varnothing 7.62 \times 7.62$ cm, and a high energy spectrometer (HES) based on $\varnothing 12 \times 15$ cm $\text{CsI}(\text{Tl})$ scintillator. Thanks to the n/γ discrimination capability of a $\text{CsI}(\text{Tl})$ crystal, HES is also intended for neutron registration. The detailed description of the instrument is represented in [2].



In this paper we mainly consider the results of the Monte Carlo simulation of the GRIS detectors response to the solar flare SOL2002-07-23 (X4.8) that was measured by RHESSI [3]. The simulation was performed in order to estimate LES and HES sensitivities to the γ -lines of the flare spectra, to prove the selection of the scintillator type for the LES detector between $\text{LaBr}_3(\text{Ce})$ and CeBr_3 and to determine the acceptable energy thresholds for both spectrometers.

The $\text{LaBr}_3(\text{Ce})$ crystal has a better energy resolution (about 3% @ 662 keV versus 4.3% for CeBr_3) but higher intrinsic activity (1.24 counts/s/cm³ versus 0.02-0.04 counts/s/cm³ of CeBr_3) [4,5]. As discussed in [4] such high activity of $\text{LaBr}_3(\text{Ce})$ may affect detection sensitivity, so a CeBr_3 crystal would be a better choice for a spectrometer in spite of its lesser energy resolution. However [5] considers additional factors: cosmic background radiation and the energy range of a detector in order to prove $\text{LaBr}_3(\text{Ce})$ as a crystal for a hard X-ray spectrometer of the PING-M instrument. Here we use a similar approach, but take into account some aspects of solar flare registration.

2. Simulation details

SOL2002-07-23 (X4.8) was chosen for the simulation of GRIS detectors response for a few reasons. First of all the spectrum parameters of this flare were described in detail in a number of publications [6-9]. The strong signature of the nuclear gamma-lines in the spectrum of the flare is the second reason. Also this event can be considered as a typical example of a high magnitude solar flare, so it can be used for the estimation of the expected maximum count rates of the detectors.

The model of the flare spectrum developed for the simulation includes several components: bremsstrahlung radiation obtained from [6,7], narrow nuclear lines [8], annihilation [7] and n-capture lines [9]. The mean energies and relative intensities of broad nuclear lines were taken from [10] and their total fluence was calculated as a difference between the total nuclear lines fluence from [7] and the fluence of narrow lines [8]. For the simulation of cosmic background was used the background model for the equatorial region of the ISS orbit described in [2] with added electron and positron albedo fluxes [11-13].

We used GEANT4 [14] as a simulation toolkit. The mass model of the GRIS detector unit with dimensions, mass and chemical composition corresponded to the real apparatus was developed. For taking into account the mass distribution within a radius of 10 m from the GRIS detector unit some of the space station modules were also included in the mass model.

The energy resolution of the detectors was imitated by the Gaussian blurring of deposited spectra. We used the energy dependences measured with the detectors prototypes in the range of 0.5-7.6 MeV:

$$R_{\text{LaBr}_3(\text{Ce})}^2 = \frac{5.5 \times 10^3}{E} + 1.9 \quad (1)$$

$$R_{\text{CeBr}_3}^2 = \frac{8.7 \times 10^3}{E} + 5.0 \quad (2)$$

$$R_{\text{CSl(Tl)}}^2 = \frac{25.1 \times 10^3}{E} + 2.7 \quad (3)$$

Where R is a FWHM (%) of a corresponding crystal and E is a deposited energy (keV) in it.

The constant terms of the equations are determined by detector inhomogeneity (light yield and light collecting inhomogeneity, etc) and not depend on the absolute light yield of a crystal. The relatively high value of the constant term for CeBr_3 (equation 2) is caused by the crystal sample $\varnothing 5.1 \times 1.25$ cm used for the resolution measurements. The light collecting homogeneity of such a crystal is not perfect due to its geometry. We can expect much better homogeneity (and much smaller constant term) for a crystal with diameter equals to its height (like $\text{LaBr}_3(\text{Ce})$ in equation 1). The descriptions of the GRIS detectors prototypes used for the measurements can be find in [2,5].

3. Simulation results

The simulation results are represented in figure 1. The most intensive γ -lines are clearly seen in the spectra of both spectrometers. It also can be seen that the flare deposited spectrum (curve 1) exceeds the cosmic background (curve 3) in the range up to 2 MeV. $\text{LaBr}_3(\text{Ce})$ intrinsic activity increases the

background count rate in the range of 0.7-3 MeV (curve 4) and leads to decreasing of the LES detector sensitivity to the most of γ -lines.

In order to estimate the sensitivities of the GRIS detectors we calculated a statistical significance for each of the γ -lines as a ratio of γ -peak counting statistics to a square root of the pedestal, which consists of the continuum component of a flare spectrum and background. The $\text{LaBr}_3(\text{Ce})$ and CeBr_3 options of LES showed similar results: neither better energy resolution (due to self-width of the liens), nor low intrinsic activity (due to the large continuum component) gave any significant advantage for the most lines. HES has about two times better γ -lines sensitivity than LES due to its large area.

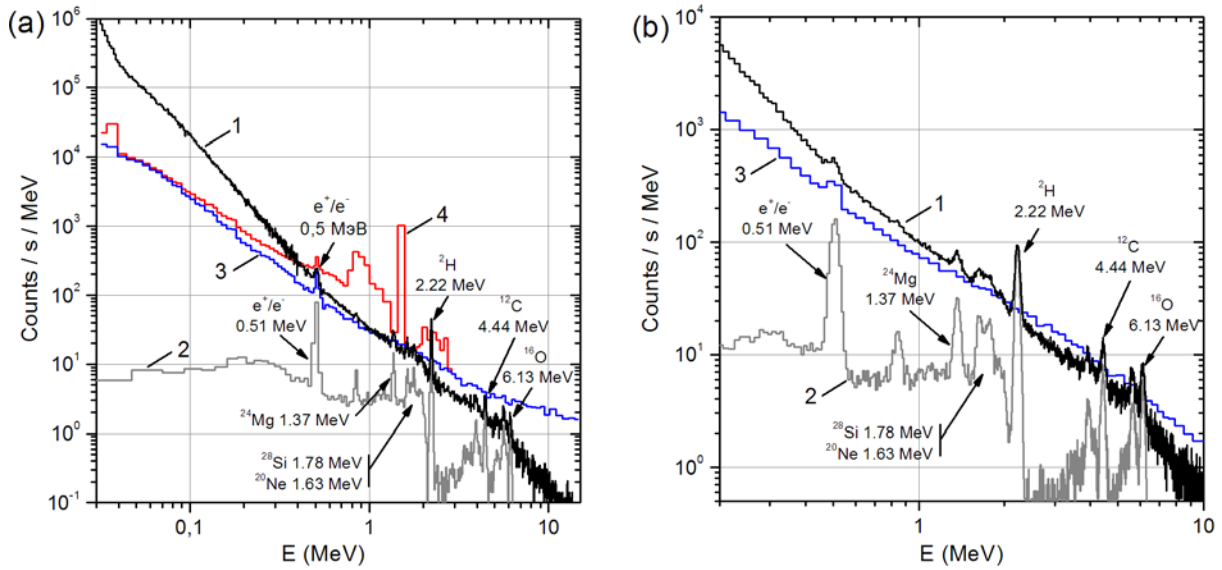


Figure 1 The simulation response of the $\text{LaBr}_3(\text{Ce})$ option of LES (a) and HES (b) to SOL2002-07-23 (X4.8): 1 – the flare deposited spectra, 2- the contribution of narrow γ -lines only, 3 – the cosmic background contribution at the equator, 4 – the sum of cosmic background and $\text{LaBr}_3(\text{Ce})$ intrinsic activity.

The much more sensitive to energy resolution task of the GRIS experiment is the measurement of narrow nuclear γ -lines redshifts. According to [8] necessary precision of line position measuring has to be not worse than 0.1-0.5%. For the estimation of measuring error we used the equation:

$$\sigma_{\bar{E}} = \frac{\sqrt{\sum (N_i + B_i) (E_i - \bar{E})^2}}{P} \quad (4)$$

Where \bar{E} is an estimate of the centre of a peak, $\sigma_{\bar{E}}$ is a sample standard deviation of \bar{E} , P is counting statistics of a peak, N_i is total counting statistics in i -th channel, B_i is an estimate of pedestal counting statistics in i -th channel, E_i is the energy corresponding to i -th channel.

The calculated errors for the γ -lines of SOL2002-07-23 (X4.8) are represented in figure 2. It can be seen that the $\text{LaBr}_3(\text{Ce})$ option of LES is 1.5-2 times better than the CeBr_3 option for >1 MeV lines. $\text{LaBr}_3(\text{Ce})$ intrinsic activity affects the less energetic lines and the errors of both options have similar values for these lines. Also it should be noted, that the constant terms of the equations 1-3 are the main contributors to total energy resolution for most energetic lines 4.4 MeV (^{12}C) and 6.1 MeV (^{16}O). Relatively high value of the constant term in equation 2 causes the CeBr_3 option disadvantage. As mentioned above we can expect similar values of the constant terms for $\text{LaBr}_3(\text{Ce})$ and CeBr_3 crystals with size of $\varnothing 7.6 \times 7.6$ cm and therefore the similar errors of 4.4 MeV (^{12}C) and 6.1 MeV (^{16}O) lines energy measurements for both options of LES. In spite of its poor energy resolution, the HES detector shows comparable to $\text{LaBr}_3(\text{Ce})$ errors for the low energy γ -lines and much better precision for 4.4 MeV (^{12}C) and 6.1 MeV (^{16}O) lines.

Figure 2 also represents the redshifts of the narrow nuclear lines measured by RHESSI in SOL2002-07-23 (X4.8) and RHESSI measuring errors, both are taken from [8]. It's easy to note that the most energetic 4.4 MeV (^{12}C) and 6.1 MeV (^{16}O) lines have the shifts that significantly exceed the LES and HES measuring errors. The reliable measurements of the redshifts of the less energetic lines are hardly possible for the GRIS instrument. Due to its very high energy resolution RHESSI has much smaller measuring errors for the most of the lines except of 4.4 MeV (^{12}C) and 6.1 MeV (^{16}O) where HES shows better precision.

The relatively high energy resolution of both options of LES provides advantage over HES in case of close lines 1.6 MeV (^{20}Ne) and 1.8 MeV (^{28}Si), which are not resolved in the HES deposited spectrum and clearly split in the LES spectrum (see figure 1).

The spectrum of SOL2002-07-23 (X4.8) is steeper than the background spectrum (see figure 1). Similar behavior persists for most of the weaker flares. Therefore the lowering of energy thresholds can increase the sensitivity of detectors to low magnitude flares. But too low thresholds may lead to counting rate saturation during high magnitude solar flares. To determine the optimal thresholds for the GRIS detectors we estimated the maximum count rates and dead times of the spectrometers for SOL2002-07-23 (X4.8) using the time curves represented in [15]. The LES maximum count rate equals 2×10^4 counts/s for a low energy threshold of 30 keV and about 10^5 counts/s for 20 keV (2 and 10% dead time correspondently for a pulse dead time of 1 μs). The HES count rate is 4×10^3 counts/s for a threshold of 200 keV and about 6×10^3 counts/s in case of 100 keV threshold (4 and 6% dead time correspondently for 10 μs for a pulse dead time of 10 μs).

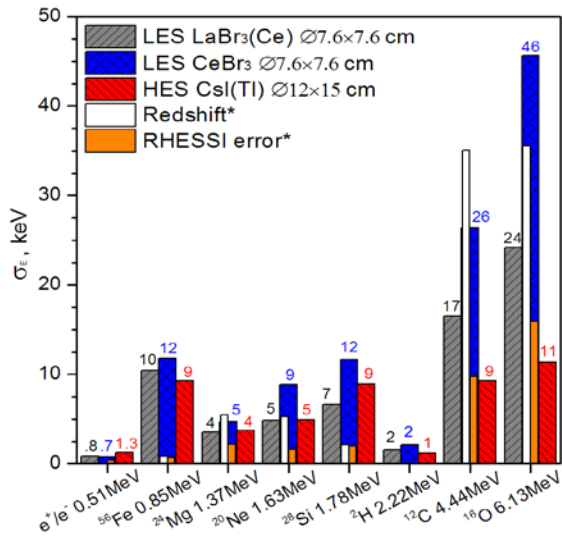


Figure 2 The γ -lines measuring errors of the GRIS and RHESSI detectors for SOL2002-07-23 (X4.8), as well as the redshifts of that lines.
* – taken from [8].

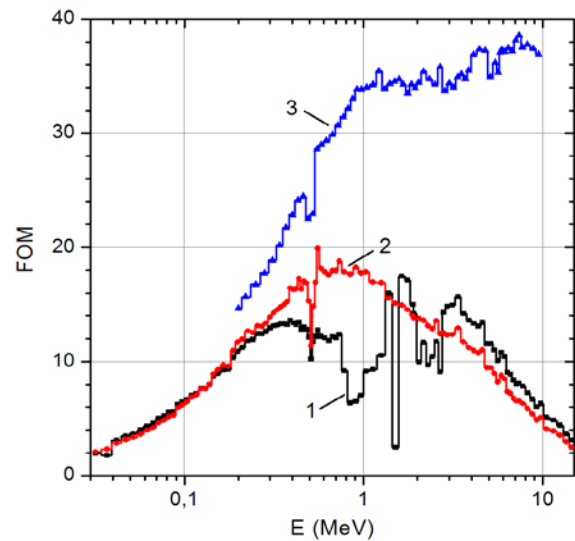


Figure 3 The GRIS detectors sensitivity comparison: 1 – LaBr₃(Ce) and 2 – CeBr₃ options of LES, 3 – HES (see the text for details).

4. LaBr₃(Ce) vs CeBr₃ detection sensitivity

X-class solar flares are relatively rare events that happen a few tens of times per a solar cycle. Therefore the most frequent feed for the GRIS spectrometers will be medium and weak flares with the energy spectra don't exceed a few hundred keV. That's why the LES sensitivity to low magnitude flares is one of the key parameters of the instrument. To estimate this sensitivity, let's consider a figure of merit (*FOM*) taken from [4]:

$$FOM(E, t) = I(E) S_{phot}(E) \sqrt{\frac{t}{B(E)R(E)}} \quad (5)$$

Here I is an incident flux of solar radiation in the range of $(E; E+dE)$, S_{phot} is photoabsorption effective area of a detector, t is an accumulation time, B is the background count rate from figure 1, R is the energy resolution of the detectors from the equations 1-3 but expressed in keV. FOM has a meaning of the statistical significance of a measuring flux (I) in the presence of background (B).

Figure 3 represents FOM s for both LES options and HES calculated for I of 1 count/s/cm² and t of 1s. It can be seen that both LES options have the same sensitivity up to 300 keV except the region of 36 keV line of LaBr₃(Ce) intrinsic activity, where a notable difference of about 1.5 times takes place. CeBr₃ gets a significant advantage in the range of 0.3-3 MeV, where the LaBr₃(Ce) intrinsic activity exceeds the cosmic background counting rate. Slightly greater FOM of the LaBr₃(Ce) option of LES above 3 MeV is mainly determined by the constant terms of the energy resolution equations 1-2, and as previously stated it doesn't depend on a crystal type.

Thus neither LaBr₃(Ce) nor CeBr₃ option of LES has significant advantages over each other. The only preference of LaBr₃(Ce) is a better (but not sufficient) precision of low energy γ -lines measuring. Since the higher sensitivity to low magnitude flares seems to us more meaningful advantage, CeBr₃ should be chosen as the crystal of the LES detector.

5. Conclusion

The simulation of GRIS response to the solar flare SOL2002-07-23 (X4.8) showed that LES and HES have the performances allowing to measure the redshifts of the most energetic γ -lines 4.4 MeV (¹²C) and 6.1 MeV (¹⁶O). We can expect similar measuring errors for this lines for LaBr₃(Ce) and CeBr₃ options of LES and much better precision for HES due to its large area and high (for CsI(Tl) crystals) resolution.

The lowering of the energy thresholds to 20 keV for LES and to 100 keV for HES increases the sensitivity of the detectors to low magnitude flares and doesn't has a risk of counting rate saturation during as high magnitude solar flares as SOL2002-07-23. Much more powerful events are possible but extremely rare events [16].

Between LaBr₃(Ce) and CeBr₃ scintillators the second one is a preferable option for the LES detector due to its lower background in the range of 0.3-3 MeV that increases the LES sensitivity to low and medium magnitude flares.

Acknowledgements

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