Simulations and Measurements of the Background Encountered by a High-Altitude Balloon-Borne Experiment for Hard X-ray Astronomy

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ABSTRACT

We have modelled the hard X-ray background expected for a high-altitude balloon flight of the Energetic X-ray Imaging Telescope Experiment (EXITE2), an imaging phoswich detector/telescope for the 20–600 keV energy range. Photon and neutron-induced contributions to the background are considered. We describe the code and the results of a series of simulations with different shielding configurations. The simulated hard X-ray background for the actual flight configuration agrees reasonably well (within a factor of ~ 2) with the results measured on the first flight of EXITE2 from Palestine, Texas. The measured background flux at 100 keV is $\sim 4 \times 10^{-4}$ counts cm^{-2} s^{-1} keV^{-1}.

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1. Introduction

Hard X-ray ($\sim$ 20-600 keV) detectors for space-based astronomy encounter background arising from various forms of ionizing radiation and their interactions with the surrounding payload and the detector itself. Because detection sensitivities are strongly dependent on this background, it must be carefully considered in the design of these instruments and interpretation of data. As part of the process of optimizing the design of the second Energetic X-ray Imaging Telescope Experiment (EXITE2) [1, 2], we developed a Monte-Carlo simulation code which calculates the expected in-flight background. The program propagates incident photons through the payload, determines the spectral and spatial distributions of photons which enter the detector, incorporates the detector response, and produces the energy spectrum of detected photon-induced background events. A separate code estimates the neutron-induced background. Because a variety of detector and shielding configurations were to be considered for optimization, we designed the program so that the spatial and energy characteristics of the incident photon spectrum and the materials and geometry of the payload are all specified in straightforward input parameter files which can be easily modified. The background simulation does not include charged-particle events, which are efficiently rejected by either the upper-level discriminator or by the active shields, as demonstrated by previous in-flight measurements made by the EXITE1 detector [3, 4].

Here we summarize the EXITE2 payload (§2), describe the Monte-Carlo simulation (§3), detail predicted backgrounds for a variety of payload configurations (§4), and then compare the predicted background, for the appropriate configuration, to data (§5) acquired during the June 1993 engineering test flight of EXITE2 from Palestine, Texas.

2. EXITE2 Payload

A schematic of the EXITE2 payload in the flight configuration is shown in Figure 1. Full details of the original EXITE2 detector configuration, as used to obtain the flight background data discussed here (§5), are given in [2], and only a brief summary is mentioned here. The detector itself is located between the collimator and the photomultiplier tube

(PMT) array and consists of a 36 cm $\times$ 36 cm $\times$ 1 cm thick NaI(Tl) crystal surrounded on five sides by 2 cm of CsI(Na), with a 0.25 mm thick aluminum entrance window and a 1.905 cm thick glass exit window. Thus, the detector as a whole is 40 cm $\times$ 40 cm $\times$ 4.93 cm. The detector and front-end electronics are enclosed in a sealed vessel pressurized to slightly above 1 atm, with a 0.35 mm thick Mylar entrance window, which is pressure-supported by the overlying collimator assembly.

The collimator consists of 52 interlocking blades (26 aligned in each orthogonal direction) spaced 1.6 cm apart (center-to-center) and each a laminate composed of a 0.9 mm layer of lead sandwiched between two 0.2 mm layers of 260 brass (70% copper, 30% zinc). The collimator field of view is 4.7° (FWHM). The mask pixels are each 1.6 cm $\times$ 1.6 cm, commensurate with the collimator cells, and are a graded stack with 12 mm lead, 1 mm tin, and 1 mm copper. The mask is supported by two pieces of 1.5 mm thick Lexan which sandwich the mask pixels. With a mask-detector distance or focal length of 2.5 m, the telescope has an angular resolution of $22'$.

The side and rear passive shields consist of 3.175 mm lead, 2 mm tin, and 1 mm copper. Active shielding composed of 1.588 cm thick NE102 plastic scintillator surrounds most of the sides and rear of the detector and is used to reject charged-particle background. The active shields are each read out by a single two-inch diameter PMT (Hamamatsu R1306) optically coupled through a light guide and edge readout.

The main detector readout consists of a 7 $\times$ 7 array of PMTs (Hamamatsu R1534). The pulse rise time of each event is measured and used to distinguish between events absorbed in the NaI(Tl) and those absorbed in the CsI(Na). The detector is continuously calibrated using a system of twelve light-emitting diodes (LEDs) whose pulsed ($\sim$ 10 Hz each) light enters the detector from the rear through optical fibers, four ^{241}Am sources which are built into the bottom of the collimator near the four corners of the detector, and periodic ($\sim$ 130 Hz) digitizations of the individual-channel baselines ("CAL events") to monitor the offsets and overall detector baseline. In addition, when the telescope is in the stowed position, the detector is partially illuminated by a ^{109}Cd source mounted above, on the gondola.

3. Simulating the Detector Background

The sources of detected background in balloon-borne hard X-ray detectors are reviewed in detail by Gehrels [5] and Dean *et al.* [6]. We include the effects of atmospheric and cosmic gamma rays, and atmospheric and locally produced neutrons. Details are given in the following subsections.

3.1. Photon-Induced Background

The photon-induced background is modelled by a two-part simulation code. The first part of the code consists of a photon-transport program, *phot_trans* (developed initially at the Massachusetts Institute of Technology and then by us at Harvard), which takes input spectral and spatial distributions of gamma rays and from these generates the spectral and spatial distributions of photons incident on the actual detector. For the input spectrum, we use the one given by Gehrels [5], which is based on data obtained at balloon altitudes ($\sim$ 3.5 g cm^{-2} residual atmosphere) over Palestine, Texas. The incident photons are assumed to be isotropic, which is a good approximation [5]. A simplified flow diagram of *phot_trans* is shown in Figure 2.

The *phot_trans* code takes into account K-shell fluorescence following photoelectric absorption. It includes K_α and K_β lines, which dominate, and neglects higher-order K lines as well as lower energy (e.g., L shell) transitions. The total fluorescence yields assumed are those given by Krause [7]. The relative intensities of the individual fluorescence lines are those given by Kaye and Laby [8]. The L and higher-order fluorescence lines have energies which are much lower than the K-line energies (e.g., $\sim$ 10–15 keV vs. $\sim$ 73–87 keV, for lead) and outside the energy range of interest for our experiment. We therefore neglect L and higher-order fluorescence. The Auger effect is neglected because Auger electrons rapidly lose their energy in traversing the material of origin and do not cause significant X-ray emission. *phot_trans* uses Compton-scattering cross sections derived from the Klein-Nishina formula for unpolarized radiation [9]. The code is fully three-dimensional and allows for any materials and configuration (e.g., detector frame and housing, side shields) around the detector.

The photons which arrive at the detector are then detected by a simulation code, based on EGS4 [10, 11], which determines the positions and amounts of energy deposition in the detector. The known detector response, which has been measured in the laboratory at several energies using collimated (to ~ 2 mm on the detector) ^{241}Am and ^{133}Ba sources placed at 25×25 locations on a grid of points 1.6 cm apart, is then used to produce the predicted photon contribution to the detected energy spectrum.

3.2. Neutron-Induced Background

The neutron-induced background is estimated using the semi-empirical method described by Dean *et al.* [6], which uses data from the MISO NaI(Tl) gamma-ray telescope [12]. The method first calculates the locally produced neutron flux incident on the detector resulting from cosmic-ray interactions with each part of the surrounding payload. Cosmic rays interact with nuclei in the payload materials, generating free neutrons which are emitted isotropically, some of which enter the detector. An atmospheric contribution to the neutron flux, based on the calculations by Armstrong *et al.* (1973) [13], is added to the local contribution. The induced detector background spectrum per neutron (in counts cm^{-3} s^{-1} keV^{-1} neutron^{-1}) was determined from a background measurement made by the MISO instrument, which was flown on a stratospheric balloon flight (3.5 g cm^{-2}) over Palestine, Texas. The neutron-induced background spectrum for other NaI(Tl) and CsI(Na) detectors can be estimated from the MISO results by taking into account the mass distribution of the corresponding payload and the geometry of the detector and rescaling the entire spectrum, which is approximately independent of energy below ~ 600 keV. We have used this method to estimate the neutron-induced background in the EXITE2 detector.

4. Background Predictions

The code for the photon-induced background was run for a number of possible EXITE2 shielding configurations. In particular, we investigated the effects of varying the thicknesses of layers in the mask, collimator, and passive shields, and then chose a mechanical design which yielded acceptable background characteristics while minimizing weight. The simulations included the part of the payload immediately surrounding the detector but none of the surrounding gondola structure or the MIXE1 detector [14] flown adjacent to the EXITE2 detector.

The results of twelve of the simulations, each with 10^5 photons incident on the detector in the 0.010–2 MeV energy range, are summarized in Tables 1 and 2, and Figures 3(a–d) and 4(a–d), where the area of the detector is taken to be 1600 cm^2, the geometrical area of the entire crystal assembly as viewed from the front of the detector. The results shown in these tables and figures are for photons *incident* on the detector. They do not include the detector response and are without phoswich rejection of CsI(Na) events, and thus the results given here should be more directly applicable to considerations for other payloads. The results shown in Table 1 and Figures 3(a–d) are for photons incident on *all* external surfaces of the detector (i.e., for all photons entering the detector), in order to characterize the total background incident on the detector. The results shown in Table 2 are for photons incident only on the front (cases 1–6), side (cases 7–9), and rear (cases 10–12) surfaces of the detector; from these results, it should be easier to infer the effects of individual payload shielding components. The results shown in Figures 4(a–d) are for photons incident only on the front (4[a–b]), side (4[c]), and rear (4[d]) surfaces of the detector. The binning in Figures 4(a–d) is coarser than in Figures 3(a–d) in order to improve statistics. Each "case" listed in the tables represents the same payload configuration in both tables. For example, case 1 represents the flight configuration in both tables, and case 5 represents the configuration with the collimator removed in both tables. Case 1 was done with the EXITE2 payload in the flight configuration. We varied the construction of the mask, collimator, side shields, and rear shield in cases 2–4, 5–6, 7–9, and 10–12, respectively. Although the actual collimator was made with brass sandwiching the lead, in the simulations we replaced the brass with copper, which has similar X-ray absorption properties and density but is a single element and thus easier to implement.

Each of the spectra shown in Figures 3(a–d) and 4(a–d) is made up of interacting photons which are a product of interactions in the surrounding payload, and non-interacting photons which have passed through the surrounding payload or collimator aperture without interacting with any of the material before entering the detector. In Figures 5(a–c), we show the spectra of interacting and non-interacting photons, and the sum of the two, for photons incident on the front (a), side (b), and rear (c) surfaces of the detector, based on a simulation with 10^6 photons incident on the detector from 0.010–2 MeV, with the payload in its flight configuration.

5. Background Measurements

EXITE2 was flown on an engineering test flight on 13–14 June 1993 from Palestine, Texas. Background data were accumulated while the payload was ascending to float altitude (~ 3.8 g cm^{-2}) and for several hours afterwards. These data have been analyzed and used to produce background spectra which were compared to the simulated results.

The procedure used to analyze the data was as follows. The data were divided into subintervals each corresponding to ~ 10 minutes of data. For each subinterval, the ^{241}Am, LED, and CAL-event data were used to determine the gains and offsets of the 49 PMT channels [15]. The individual-channel pulse heights were thus corrected for electronic gain and offset variations, which were small—typically $\sim 2\%$ and ~ 200 eV (i.e., 0.2% of the PMT signal amplitude in the case where a 100 keV X-ray is absorbed in the detector directly above a given PMT), respectively. Pulse-shape discrimination (PSD) was used to reject events which were absorbed in the CsI(Na). The PSD rejection efficiency (i.e., percentage of CsI[Na] events rejected while retaining at least 90% of the NaI[Tl] events) ranges from $\sim 30\%$ at 20 keV to $> 99\%$ at energies $> \sim 60$ keV and is a function of how well the NaI(Tl) and CsI(Na) pulse shapes can be distinguished from each other at different signal amplitudes. The number of detected LED events was compared to the number known to have occurred during each subinterval (at $\sim$ 120 Hz) in order to determine the electronic dead time of the system, for which a correction was made. The uncertainty in the measured background flux due to this correction is $\sim$ 15%. The pulse height for each event was converted into an energy, with a correction made for the position-dependent gain of the detector as well as the non-linear response of NaI(Tl) for its optical output as a function of energy [16].

Three background spectra were produced from the flight data and are displayed in Figures 6(a–c) along with the simulated background spectrum corresponding to the actual payload configuration. Since in our simulations we did not take into account the surrounding gondola structure (i.e., only the detector frame and shielding are included), the same simulated results are shown in all three figures. The data used to produce the background spectra in Figures 6(a–b) were acquired between 19:30 and 20:10 UT on 13 June 1993, when the telescope was approaching float ($\sim$ 5–10 g cm^{-2}) but still in the stowed (i.e., vertical) position. Position cuts were used to remove ^{241}Am source counts (from the four calibration sources) in Figure 6(b). The data used to produce the background spectrum in Figure 6(c) were acquired between 20:18 and 20:54 UT, when the telescope had reached float altitude ($\sim$ 3.8 g cm^{-2}) and was unstowed at an elevation of $\sim$ 60°, and the ^{109}Cd source was outside the field of view. Position cuts were again used to remove ^{241}Am source counts. The fluxes shown in Figures 6(a–c) correspond to an area of 1200 cm^2, which takes into account the exclusion of $\sim$ 7% of the NaI(Tl) area, where the ^{241}Am source counts lie. The simulated spectrum includes contributions from photon and neutron-induced events. The simulated photon-induced background shown in these figures is based on a simulation with 10^6 photons incident on the detector in the 0.010-2 MeV energy range.

6. Discussion

A number of conclusions can be drawn from the results shown in Figures 3(a–d) and 4(a–d). The presence of the coded-aperture mask decreases the photon-induced background. The effect becomes less pronounced at higher energies, where a larger fraction of the photons reaching the detector come from outside the collimator field of view and thus do not pass through the mask. The presence of the collimator reduces the background at all energies, with greater effectiveness at lower energies, where only photons passing through the collimator aperture can reach the detector. Covering the sides of the lead in the collimator with copper reduces the background slightly at all energies, but some lead-fluorescence from the collimator blades persists. Most of this is from the exposed ends of the collimator blades, because the copper in the simulations, like the brass in the actual collimator, does not extend over the ends of the blades, but, like the lead, is flush with the detector pressure vessel entrance window; see additional discussion below. Figures 3(b) and 4(b) include an additional case, not listed in the tables, in which the collimator consists only of lead and has had its pitch changed from 1.6 cm to 5.5 cm so that the field of view is $\sim 15°$. The resulting background spectrum contains a much more pronounced lead-fluorescence peak (19 σ vs. 4 σ, in Figure 3[b]), in reasonable agreement with the results obtained by Schindler *et al.* [17] for the Caltech detector with a similarly constructed lead collimator. Our results indicate that additional shielding of the collimator lead would be warranted for instruments with wider fields of view. The side and rear shields reduce the background at all energies, as expected. The results in Figure 4(d) illustrate the importance of building a graded lead-tin-copper rear shield, where the tin blocks lead fluorescence and the copper blocks tin fluorescence.

The spectra in Figures 5(a–c) show that at low energies ($\sim$ 20-40 keV) the photon-induced background incident on the detector is completely dominated by non-interacting photons which arrive at the front of the detector through the collimator aperture. The non-interacting component shown in Figure 5(a) below $\sim$ 200 keV represents the "aperture flux" background which enters through the collimator. At higher energies, the non-interacting component in Figure 5(a) is dominated by photons which pass through collimator material, without interacting, and reach the detector. Figure 5(a) also shows the lead fluorescence lines at 75 keV and 85 keV which are from the lead in the collimator blades. The interacting components in Figures 5(b–c) represent the "shield leakage" background and consist of incident and locally produced X-rays and gamma-rays which leak through the shields and detector housing, and enter the detector.

The lead-fluorescence fluxes shown in Table 2 (which include photons entering the detector through the front [cases 1–6], side [cases 7–9], and rear [cases 10–12] surfaces only) indicate that there would be significant contributions from the mask (case 3), collimator (case 6), side shields (case 8), and rear shield (case 11) if the lead were not covered by tin. Comparison of the 75 keV fluxes shown for cases 1, 3, and 4 shows that adding the copper to the mask elements reduces the detected lead fluorescence so that it is consistent with the no-mask case (case 2). The relatively weak lead-fluorescence detection through the side detector surfaces (case 8) is due to the low probability that a sufficiently energetic photon will be photoelectrically absorbed in the side-shield lead and result in the emission of a fluorescence photon which subsequently enters the detector through one of the side surfaces; most of these lead-fluorescence photons would have a higher probability of entering the detector through the front or rear surfaces, because of the larger solid angles they subtend as viewed from most points on the side shields. The 75 keV line flux which is detected in the flight configuration (case 1) is due to the lead in the collimator blades and could be reduced by adding more shielding on top of the lead, at the expense of reducing the open collimator area. The tin-fluorescence fluxes shown in Table 2 indicate that, without copper shielding, there would be significant contributions from the mask (case 4) and rear shield (case 12), but not from the side shields (case 9). The tin-fluorescence flux and upper limits listed for cases 1–6 in Tables 1 and 2 are the same because, for these payload configurations, the only photons reaching the detector arrive on the front surface. The 100 keV continuum fluxes shown in Table 1 are all comparable to each other except for the cases with the collimator (case 5), side shields (case 7), or rear shield (case 10) removed, where they are significantly higher.

As shown in Figures 6(a–c), the total simulated background spectrum agrees reasonably well (within a factor of ~ 2, when the ^{241}Am calibration source counts are removed) with the measured spectra. The differences between the simulated and measured spectra can be attributed to our simplified representation (e.g., neglect of the surrounding gondola structure and MIXE1 detector) of the payload and other approximations such as using input spectra which were derived from data acquired at a specific altitude and location, even though the actual coordinates of the EXITE2 payload differed somewhat during its flight. In addition, a high voltage related noise problem present during flight (but not while the payload was on the ground) degraded our PSD performance, particularly at the lower energies ($< \sim 60$ keV), preventing us from making more restrictive rise-time cuts which would have reduced the residual background at these energies. The cause of this problem has since been identified and fixed.

With the telescope stowed, the measured background at 100 keV is $\sim 4 \times 10^{-4}$ counts cm^{-2} s^{-1} keV^{-1}, which agrees closely with the simulated results and is slightly lower than the background measured by the Caltech group [17] for an imaging phoswich detector above Alice Springs, Australia. The Caltech detector has a larger field of view than the EXITE2 detector (15° vs. 4.7°, FWHM), making its aperture-flux background higher. We note that the difference in geomagnetic latitude between Alice Springs and Palestine normally yields background rates a factor of ~ 2 lower in Alice Springs. With the telescope unstowed, the measured background at 100 keV is $\sim 2.5 \times 10^{-4}$ counts cm^{-2} s^{-1} keV^{-1}. The measured background is generally higher with the telescope stowed due to increased Compton scattering into the field of view from the gondola structure above the detector, as well as the generally higher background environment associated with the lower altitude at which the stowed data were obtained. The atmospheric 511 keV line is barely detectable above the continuum and appears as a slight excess in the measured spectra. The observed intensity of the line is consistent with the flux measured by Schindler *et al.* [17], given the smaller field of view of the EXITE2 telescope. The line is not included in the simulated results.

The flux sensitivity of a coded-aperture telescope, in the applicable limit where the detector background counting rate is much larger than the counting rate due to the astrophysical source, is given by

$$F_K = \frac{2K}{\eta\epsilon t_a t_i t_c (1 - t_m)} \sqrt{\frac{B}{A\tau\Delta E}} \tag{1}$$

where F_K is the source flux, in photons cm^{-2} s^{-1} keV^{-1}, which can be detected with statistical significance K; η is the imaging efficiency, a factor ($< \sim 1$) which accounts for the loss of sensitivity due to finite detector spatial resolution (at any given energy) relative to the coded-aperture mask cell size [18]; ϵ is the photon full-energy detection efficiency; t_a is the fraction of source photons transmitted through the overlying atmosphere; t_i is the fraction of source photons transmitted through passive material in the instrument (i.e., the aluminum detector entrance window and the Lexan coded-aperture support sandwich); t_c is the fraction of source photons transmitted through the collimator and is taken as 0.844 for normal incidence; t_m is the fraction of source photons transmitted through closed coded-aperture cells; B is the detector background counting rate, in counts cm^{-2} s^{-1} keV^{-1}; A is the geometrical usable area of the detector, in cm^2; τ is the observation time in seconds; and ΔE is the width, in keV, of the energy band for the flux measurement.

The 3 σ detection sensitivity, based on the simulated background spectrum, is plotted as a function of energy in Figure 7, assuming 4.0 g cm^{-2} residual atmosphere along the line of sight (corresponding to 3.5 g cm^{-2} residual atmosphere and a telescope elevation of $\sim 60°$), 10^4 s observation time, and an energy bandwidth ΔE equal to 50% of the energy. The sensitivity is plotted for NaI(Tl) alone and for NaI(Tl) and CsI(Tl) combined (i.e., with PSD turned on and off, respectively). At 100 keV, PSD rejection is found to reduce the instrument background by a factor of ~ 3 and to improve the sensitivity by a factor of ~ 1.5. At energies above ~ 215 keV, it is advantageous to retain CsI(Na) events since the additional background is more than compensated for by the additional stopping power of the CsI(Na), resulting in improved sensitivity.

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Fig. 1.— EXITE2 payload schematic. Approximately to scale except for the detector-to-mask distance.

Fig. 2.— *phot_trans* flow diagram.

Fig. 3.— Simulated photon-induced background showing individual effects of the (a) mask, (b) collimator, (c) side shields, and (d) rear shield on the spectrum of photons incident on all sides of the detector, not including the detector response and without PSD rejection. The lead-fluorescence emission shown in (a) at 75 keV is due primarily to the collimator (see text). Included in (b) is an additional case, not listed in the tables, in which the collimator consists of lead only and has had its pitch changed from 1.6 cm to 5.5 cm so that the field of view is $\sim 15°$. The resulting background spectrum (long-dashed line) contains a much more pronounced lead-fluorescence peak originating from the sides of the collimator blades.

Fig. 4.— Simulated photon-induced background showing (a) mask, (b) collimator, (c) side-shield, and (d) rear-shield effects on the spectrum of photons incident only on the front (a–b), side (c), and rear (d) detector surfaces.

Fig. 5.— Simulated photon-induced background showing the total spectrum (solid line) of photons incident on the front (a), side(b), and rear (c) surfaces of the detector, not including the detector response and without PSD rejection, and contributions from interacting (dashed line) and non-interacting (dotted line) photons for the flight configuration (case 1). Interacting photons have interacted with the surrounding payload before reaching the detector; non-interacting photons have not.

Fig. 6.— Measured (data points) and simulated backgrounds, showing the total simulated background (solid line) and its contributions from photon-induced events (dashed line) and neutron-induced events (dotted line). Uncertainties in the measured fluxes are $< \sim 5\%$. The data shown in (a) and (b) were acquired with the telescope in the stowed position. The data shown in (c) were acquired with the telescope unstowed at an elevation of $\sim 60°$. The measured spectrum in (a) includes contributions from the ^{241}Am and ^{109}Cd calibration sources at 60 keV and 88 keV. In (b) and (c), the contribution from the ^{241}Am sources has been removed. In (c), the 88 keV ^{109}Cd source is no longer in the field of view. The atmospheric 511 keV line is barely detectable in the data and appears as a slight excess at $\sim$ 500 keV; the line is not included in simulated results. The simulated results in (a–c) are all the same since the surrounding gondola structure was not included in simulations.

Fig. 7.— Detection sensitivity vs. energy, showing the 3 σ sensitivity for NaI(Tl) alone (solid line) and for NaI(Tl) and CsI(Na) combined (dashed line) (i.e., with PSD turned on and off, respectively), based on the simulated background, assuming 4.0 g cm^{-2} residual atmosphere along the line of sight, 10^4 s observation time, and an energy bandwidth ΔE, for a hypothetical flux measurement, equal to 50% of the energy. The spectrum of the Crab Nebula [19] at one-tenth of its true intensity is also shown for comparison.

Case	Payload Configuration	F_{25keV} (ph cm^{-2} s^{-1})	F_{75keV} (ph cm^{-2} s^{-1})	F_{100keV} (ph cm^{-2} s^{-1} keV^{-1})
1	111 11 111 111	$< 3.70 \times 10^{-5}$	$(6.44 \pm 1.56) \times 10^{-4}$	$(1.13 \pm 0.05) \times 10^{-3}$
2	000 11 111 111	$< 5.40 \times 10^{-5}$	$(7.27 \pm 1.64) \times 10^{-4}$	$(1.11 \pm 0.05) \times 10^{-3}$
3	100 11 111 111	$< 3.33 \times 10^{-5}$	$(6.40 \pm 1.57) \times 10^{-4}$	$(1.14 \pm 0.05) \times 10^{-3}$
4	110 11 111 111	$(1.31 \pm 0.30) \times 10^{-4}$	$(7.48 \pm 1.58) \times 10^{-4}$	$(1.08 \pm 0.05) \times 10^{-3}$
5	111 00 111 111	$< 2.52 \times 10^{-3}$	$< 2.93 \times 10^{-3}$	$(8.38 \pm 0.32) \times 10^{-3}$
6	111 10 111 111	$< 3.71 \times 10^{-5}$	$(8.28 \pm 1.63) \times 10^{-4}$	$(1.16 \pm 0.05) \times 10^{-3}$
7	111 11 000 111	$< 2.66 \times 10^{-4}$	$(1.26 \pm 0.45) \times 10^{-3}$	$(3.29 \pm 0.11) \times 10^{-3}$
8	111 11 100 111	$< 3.90 \times 10^{-5}$	$(8.61 \pm 1.73) \times 10^{-4}$	$(1.13 \pm 0.05) \times 10^{-3}$
9	111 11 110 111	$< 4.24 \times 10^{-5}$	$(5.54 \pm 1.59) \times 10^{-4}$	$(1.12 \pm 0.05) \times 10^{-3}$
10	111 11 111 000	$< 5.27 \times 10^{-5}$	$(1.00 \pm 0.33) \times 10^{-3}$	$(3.12 \pm 0.10) \times 10^{-3}$
11	111 11 111 100	$< 3.52 \times 10^{-5}$	$(4.28 \pm 0.21) \times 10^{-3}$	$(1.08 \pm 0.05) \times 10^{-3}$
12	111 11 111 110	$(1.66 \pm 0.09) \times 10^{-3}$	$(6.01 \pm 1.55) \times 10^{-4}$	$(1.13 \pm 0.05) \times 10^{-3}$

Table 1: Simulated photon-induced background. For each shielding configuration, the table lists which payload components (mask lead, tin, and copper; collimator lead and copper; side-shield lead, tin, and copper; rear-shield lead, tin, and copper) are present (indicated by a "1" in the corresponding column; for example, case 3 has the mask lead present, mask tin and copper both absent, and all other components present), and the tin-fluorescence line flux or 2 σ upper limit (in photons cm^{-2} s^{-1}, with the K_{α_1} and K_{α_2} lines at $\sim$ 25 keV combined) incident on the detector, lead-fluorescence line flux or 2 σ upper limit (K_{α_1} line at $\sim$ 75 keV), and continuum flux (in photons cm^{-2} s^{-1} keV^{-1}) at 100 keV, with 1 σ uncertainties also listed. Uncertainties are based on Poisson noise considerations and could have been reduced by running longer simulations.

Case	Payload Configuration	F_{25keV} (ph cm^{-2} s^{-1})	F_{75keV} (ph cm^{-2} s^{-1})	F_{100keV} (ph cm^{-2} s^{-1} keV^{-1})
1	111 11 111 111	$< 3.70 \times 10^{-5}$	$(3.72 \pm 0.49) \times 10^{-4}$	$(4.39 \pm 0.92) \times 10^{-5}$
2	000 11 111 111	$< 5.40 \times 10^{-5}$	$(3.70 \pm 0.56) \times 10^{-4}$	$(3.67 \pm 0.84) \times 10^{-5}$
3	100 11 111 111	$< 3.33 \times 10^{-5}$	$(5.26 \pm 0.58) \times 10^{-4}$	$(4.23 \pm 0.90) \times 10^{-5}$
4	110 11 111 111	$(1.31 \pm 0.30) \times 10^{-4}$	$(4.48 \pm 0.53) \times 10^{-4}$	$(4.42 \pm 0.92) \times 10^{-5}$
5	111 00 111 111	$< 2.52 \times 10^{-3}$	$< 2.81 \times 10^{-3}$	$(7.34 \pm 0.31) \times 10^{-3}$
6	111 10 111 111	$< 3.71 \times 10^{-5}$	$(6.07 \pm 0.63) \times 10^{-4}$	$(3.16 \pm 0.79) \times 10^{-5}$
7	111 11 000 111	$< 8.52 \times 10^{-6}$	$< 3.39 \times 10^{-4}$	$(5.18 \pm 0.44) \times 10^{-4}$
8	111 11 100 111	$< 4.62 \times 10^{-6}$	$(1.80 \pm 0.60) \times 10^{-4}$	$(1.04 \pm 0.15) \times 10^{-4}$
9	111 11 110 111	$< 4.45 \times 10^{-6}$	$< 1.03 \times 10^{-4}$	$(8.70 \pm 1.30) \times 10^{-5}$
10	111 11 111 000	$< 7.85 \times 10^{-6}$	$< 6.20 \times 10^{-4}$	$(2.95 \pm 0.10) \times 10^{-3}$
11	111 11 111 100	$< 4.57 \times 10^{-6}$	$(3.87 \pm 0.19) \times 10^{-3}$	$(9.26 \pm 0.43) \times 10^{-4}$
12	111 11 111 110	$(1.63 \pm 0.09) \times 10^{-3}$	$< 2.74 \times 10^{-4}$	$(9.64 \pm 0.43) \times 10^{-4}$

Table 2: Simulated photon-induced background. Same as Table 1, except that here fluxes are measured for photons incident only on the front (cases 1–6), side (cases 7–9), and rear (cases 10–12) detector surfaces. For cases 1–6, the tin-fluorescence flux and upper limits are the same as in Table 1, since at this energy the only photons reaching the detector arrive on the front surface, for the corresponding payload configurations.