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# Modeling of proton-induced radioactivation background in hard X-ray telescopes: Geant4-based simulation and its demonstration by *Hitomi*'s measurement in a low Earth orbit

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ABSTRACT

Hard X-ray astronomical observatories in orbit suffer from a significant amount of background due to radioactivation induced by cosmic-ray protons and/or geomagnetically trapped protons. Within the framework of a full Monte Carlo simulation, we present modeling of in-orbit instrumental background which is dominated by radioactivation. To reduce the computation time required by straightforward simulations of delayed emissions from activated isotopes, we insert a semi-analytical calculation that converts production probabilities of radioactive isotopes by interaction of the primary protons into decay rates at measurement time of all secondary isotopes. Therefore, our simulation method is separated into three steps: (1) simulation of isotope production, (2) semi-analytical conversion to decay rates, and (3) simulation of decays of the isotopes at measurement time. This method is verified by a simple setup that has a CdTe semiconductor detector, and shows a 100-fold improvement in efficiency over the straightforward simulation. To demonstrate its experimental performance, the simulation framework was tested against data measured with a CdTe sensor in the Hard X-ray Imager onboard the *Hitomi* X-ray Astronomy Satellite, which was put into a low Earth orbit with an altitude of 570 km and an inclination of 31°, and thus experienced a large amount of irradiation from geomagnetically trapped protons during its passages through the South Atlantic Anomaly. The simulation is able to treat full histories of the proton irradiation and multiple measurement windows. The simulation results agree very well with the measured data, showing that the measured background is well described by the combination of proton-induced radioactivation of the CdTe detector itself and thick $Bi_4Ge_3O_{12}$ scintillator shields, leakage of cosmic X-ray background and albedo gamma-ray radiation, and emissions from naturally contaminated isotopes in the detector system.

## 1. Introduction

Hard X-ray telescopes for astrophysics must be in orbit because of atmospheric absorption, and therefore suffer from significant backgrounds induced by cosmic rays and/or geomagnetically trapped charged particles. Direct ionization signals of the charged particles and prompt gamma-ray emissions they cause can be eliminated by the anti-coincide nce of active shields associated with primary detectors [1]. However, delayed emissions from radioactive isotopes produced by interactions with detector material of cosmic-ray protons and/or geomagnetically trapped protons remain [2,3]. These kinds of background may arise from the inside of the detectors themselves and therefore are extremely difficult to eliminate as noise since neither anti-coincidence nor collimators are effective for rejecting it. Thus, evaluation of the radioactivation background via modeling must be an important performance factor for hard X-ray observations.

Monte Carlo simulation has been an effective means of evaluating the background in a phase of mission planning since the instrumental design and the selection of orbit must depend on an estimate of the background [4–7]. It provides crucial information for optimizing the selection of detector material, arrangement of the detectors, shields and their supporting structure, and data acquisition strategies. Simulation is also necessary for estimating the background before the launch of the satellite, allowing us to develop a specific science program (astronomical observation planning).

In the data analysis phase phenomenological methods, rather than the full simulation, have typically been employed for the purpose of subtracting the background from the obtained data primarily because empirical modeling based on measured data has been considered sufficiently accurate and even more efficient. In addition, due to the complexity of hadronic processes, simulations have not necessarily achieved sufficient model accuracy. Nonetheless, a full simulation is a more promising approach because of its comprehensiveness and flexibility. Empirical methods are normally limited by various conditions such as energy bands, observation time windows, or fields of view. They are further limited by data quality and availability. Demands for comprehensive simulations will increase as instruments achieve higher resolutions and more complex structures both in hardware and software (e.g., multiple layers, a number of readout channels, and a variety of data acquisition modes).

The full simulation of radioactivation is a significantly complicated process. In addition to the difficulties associated with normal Monte Carlo simulations, such as inaccuracies of mass models, physical process implementation, and input radiation environments in orbit, it requires treatment of the delayed nature of radioactivation. Thus, the simulation must consider the entire history of the particle irradiation and integrate events over a time window of interest. MGGPOD [4] introduced an efficient scheme to solve this problem by separating the calculation into the production of radioactive isotopes and the decays of these isotopes. To connect these two phases, it is necessary to convert the production information into the decay rates of the isotopes, which can be done by analytical or numerical methods; it does not require time-consuming Monte Carlo calculations.

We have developed a new general-purpose simulation framework to evaluate radioactivation in orbit by adopting the above scheme. Our framework utilizes the Geant4 toolkit library [8–10], which is a widely used Monte Carlo simulation package, allowing full compatibility with other types of important simulations including photon signals and other backgrounds such as cosmic X-ray background, Earth's albedo gamma rays and neutrons, prompt emissions due to cosmic rays, and so on. We used Geant4, version 10.04.b01, in order to apply the latest hadronic physics models and associated databases including nuclear tables. Our code treats an arbitrary irradiation time profile in order to account for the highly variable radiation environment along the orbit.

For software verification and performance evaluation, we compared simulation results to in-orbit data obtained with the Hard X-ray Imager (HXI) [11,12] onboard the *Hitomi* X-ray astronomy satellite [13,14], which was put into a low Earth orbit (LEO). A spectrum measured by the HXI is highly suitable for this test in the energy range of 10–160 keV; the detector materials, one of which is cadmium telluride (CdTe) in its main focal plane imager, had been exposed to highly variable, high flux geomagnetically trapped protons during their passages through Earth's radiation belt, generating instrumental background dominated by proton-induced radioactivation. The Soft Gamma-ray Detector (SGD) [15,16] aboard the same satellite also provided us with useful data at higher energies up to 600 keV, though we focus on the HXI background in this paper because of less complicated structure and data reduction methods of the HXI. Data analysis of the SGD background using our simulation framework will be presented separately in future.