

Simulation for astroparticle experiments and planetary explorations: tools and applications

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Abstract

We present a set of tools and general-purpose applications for the simulation of astrophysics and astroparticle experiments, concerning both physics and radiation background studies. They address the specific requirements of various typical astroparticle detectors: new-generation X- and γ -ray detectors on satellites, underground detectors for astroparticle experiments and solar system explorations.

Keywords: Simulation Astroparticle Object oriented User requirements

1 Introduction

The simulation of particle interactions in the experimental set-up is essential to most astroparticle physics experiments: it plays a fundamental role in the design of the detector and shielding components, in the investigations of the physics capabilities of the experiment and in the evaluation of backgrounds. In particular, γ and X-ray telescopes of the new generation, such as XMM-Newton [1], GLAST [2] or AGILE [3], dark matter detectors and new planned planetary missions require an accurate and reliable simulation of primary physics events and of backgrounds, in a realistic and detailed model of the experimental environment.

Geant4 [4] is a new-generation, Object-Oriented particle transport Toolkit that allows full and fast 3-dimensional simulation in a user-defined geometry. The wide selection of physics processes over an extended energy range, the modular approach and the flexibility to describe complex experimental configurations, deriving from the adoption of the Object Oriented technology, make Geant4 an ideal system for the simulation of astroparticle experiments.

We present here the requirements for the simulation of typical astroparticle experiments and we discuss how they can be addressed by a framework based on the Geant4 Toolkit.

2 Physics Requirements for the simulation of astroparticle experiments

Space-based astroparticle experiments are designed to detect physical phenomena in the universe that are invisible from the Earth. As space-based observatories obviously cannot easily be reconfigured, repaired or maintained, it is necessary to accurately determine their detector and mass configuration and characteristics pre-launch to satisfy the scientific objectives. In particular, the main tasks include determining the background rejection methods and the evaluation of the scientific performance of the instrument. The space radiation environment near the Earth is dynamic and complex, and varies depending both on the time of mission and on the type of orbit chosen. In most cases, the main sources of background for photon detectors are the galactic cosmic rays, geomagnetically trapped particles and solar proton events. The discrimination of charged particle tracks from photon tracks is a delicate task, requiring accurate simulations and modelling of the detector and of the background itself.

Next generation Dark Matter detectors will soon come on-line with extensive physics reach covering 90% of the theoretically interesting parameter space. In addition there is interest in neutrino physics programmes that share a common dependency upon low-background underground locations. The importance of any dark matter detector is the ability to discriminate between the large levels of background events and the expected low signal rate. The majority of the background comes from γ rays from local radioactivity. However, background also comes from secondary nuclear products such as neutrons and γ s from α interactions. Dependent on the characteristic and radiation type and detector position will determine interpretation and true background. Background will exceed signal by $> 10^6$. Rare background processes, detector systematics and inhomogeneities may ultimately lead to mis-interpretation of the output. It is crucial to simulate the complete underground environment from cosmic rays to cavern via the rock between the surface and the underground detector and to reproduce background contribution from cosmic rays, local environment and construction materials and provide realistic events within the detector volume.

Planetary astrophysics experiments share similar requirements as other space missions, concerning modeling the space radiation background and its effects on the science instruments on board. Beyond the use for the evaluation of mission risks, simulation may play a significant role also in evaluating the physics reach and in optimising the detectors. An example is, for instance, ESA Bepi Colombo [5] mission to Mercury, where simulation plays an essential role in the feasibility studies for the measurement of the elemental composition of the planet by means of analysis of the fluorescence spectrum (figure 1), as well as in the optimisation of detector technologies in the presence of the severe radiation environment in the vicinity of Mercury.

3 Simulation Toolkit Capability requirements

The simulation of an astroparticle experiment should address all the issues mentioned above, with the main emphasis given to the detector configuration and to the consequences of the interactions of the particles in the environment within the configuration.

The detector should be described from the point of view of the materials used and the geometry adopted, both for the structural and for the active detecting elements. The configurations adopted for the read-out and the logic of the data acquisition on the quality of the physics results should be also modeled, in order to evaluate their impact on the overall performance of the detector.

The simulation should be able to describe the properties and the physics processes of the particles involved both in the expected signal and in the background. Especially important is the capability to handle physics processes across a wide energy range, which in such experiments simulation may span several orders of magnitude.

An ideal simulation framework should also be flexible, open to evolution and to the integration of external tools. This is particularly important for astroparticle applications, where a number of software tools are already commonly used within the scientific community and where the peculiar experimental environment may require the ability to extend the simulation functionalities, for instance including the ability to deal with peculiar physical processes.

4 The Geant4-based simulation framework

Geant4 is a general-purpose Toolkit for the simulation of the passage of particles through matter. It provides functionalities for all the typical domains of simulation: geometry, tracking, detector response, run, event and track management, Particle Data Group compliant particle management, visualisation and user interface, as well as a large variety of physics processes and models. The wide spectrum of functionalities provided make it particularly suitable for the

simulation of astroparticle experiments. Thanks to the Object-Oriented technology, Geant4 provides a high degree of flexibility and openness to evolution, as well as to the integration of external tools. Some features of Geant4 relevant to astroparticle experiments, as well as components especially developed for such applications, are summarised below.

An abstract interface to primary event generators is provided in Geant4, allowing the user to customise his/her simulation input. The General Particle Source [7] has been developed to extend the capabilities of the Geant4 Toolkit to satisfy the requirements of space applications.

The Geant4 Toolkit provides facilities to describe the geometry [6] and material composition of the experimental set-up, the equation of motion solvers in different fields, as well as the detector response resulting from the interactions of particles. An ISO STEP compliant solid modeller, allows the exchange of models from CAD systems. Multiple solid representations, such as Constructive Solid Geometry, Boundary Represented Solids are supported according to the ISO STEP standard. Such power and flexibility allows to model any experimental set-up, including also spacecraft components through their CAD description.

The Geant4 Toolkit provides an abundant set of physics processes to describe the interactions of particles with matter. Thanks to the object oriented technology, a variety of underlying models is often available for the same physics process, depending on the energy range, particle type or material. Geant4 Electromagnetic Physics [8] manages electron and positron, photon, and muon interactions, as well as the electromagnetic interactions of hadrons and ions. The validity range of all the muon processes, based on theoretical models, scales up to the 1000 PeV region, allowing the simulation of ultra-high energy and cosmic ray physics. A set of physics processes is also available in Geant4, extending the validity range of electromagnetic interactions down to low energies (< 1 keV) [9]. Such an extended energy range of electromagnetic processes is essential to astroparticle experiments, in particular underground ones. Fluorescence emission can be also simulated; such process is required for studies of the geological composition of planets, asteroids and moons.

Geant4 Hadronic Physics [10] offers both parameterisation-driven models and a variety of theory-driven models, as well as treatment of low energy neutron transport. Long-term radioactivity produced by nuclear interactions represents an important contribution to background levels in space-borne γ -ray and X-ray instruments, as the ionisation events that result often occur outside the time-scales of any veto pulse; it is also essential to background studies in underground experiments. A Radioactive Decay Module [11] is available in Geant4 to treat the emissions of α , β^\pm , n and particles, as well as the γ - and X-rays associated with α , β^\pm , electron capture and isomeric transition decays.

Geant4 Visualisation [12] and User Interface design is based on object oriented abstract interfaces, thus allowing to provide functionalities to Geant4 independently from any particular system. The simulation framework can be interfaced also to new generation, object oriented Analysis Tools systems[13], thus satisfying the typical requirement of experimental applications to produce plots and analyse the results of the simulation.

5 Discussion and Conclusions

By virtue of its Object-Oriented design and extensive coverage of physics processes, the Geant4 Toolkit provides an ideal platform for simulation of in-orbit and underground astroparticle experiments. Both the scientific performance and the radiation background effects related to such experiments can be studied in a fully 3-dimensional, user-defined geometry. In particular, these capabilities are useful for new-generation astroparticle experiments, where undesirable detector radiation background can often mask the scientific signals to be observed.

Several general-purpose Geant4 applications have been constructed to aid rapid development of full-scale simulation models for existing and future astroparticle experiments of arbi-

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Solar X-ray induced emission from basalt - M-flare

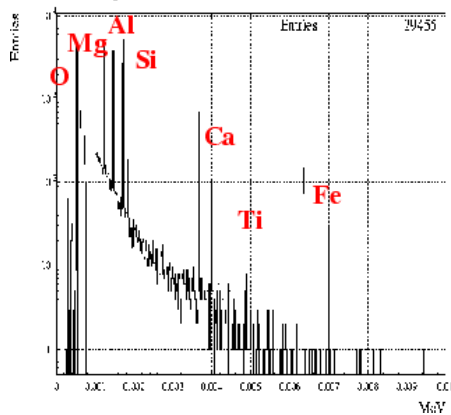


Figure 1: Simulated response from a representative composition of basalt in the case of a solar flare

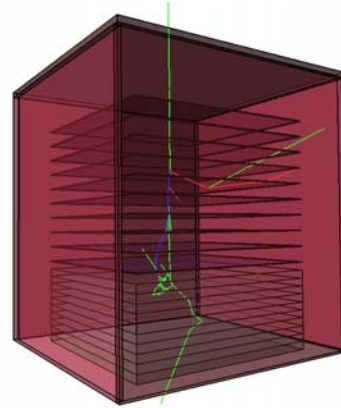


Figure 2: Geant4 model of the basic tracker, calorimeter and anticoincidence detectors of a γ -ray telescope

trary configuration. An example is shown in figure 2 for a general-purpose γ -ray telescope. In addition to the relevant physics processes, these applications include interfaces to customised Geant4 primary particle sources, and also utilise the geometry and material components of the Toolkit. General-purpose applications for the simulation of X and γ telescopes have been released with Geant4 3.0, and applications for the study of underground radiation backgrounds and for planetary explorations are in progress and will be released in future versions of the Toolkit. Such applications represent a guidance to the selection of the Toolkit components especially relevant to astroparticle experiments.

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