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Validation of electromagnetic and hadronic physical processes in the interaction of a proton beam with matter: A Solar Particle Events case study with an Al slab

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Abstract

In the study of the effectiveness of shielding materials against radiations, one of the main steps concerns with the validation of models describing the interaction processes of the radiation of interest with the material chosen for the shielding. This paper shows the results of the validation of electromagnetic and hadronic processes with the aim to contribute to the study of protection for astronauts against the radiations due to the Solar Particle Events, in particular to the selection of the optimal material for radiation shielding. The physics case deals with the interaction of a proton beam with an aluminum slab about 20 g/cm^2 thick. Two specific applications, STP and DOSE, were developed by using Geant4 package. STP computes the radiations produced in the interaction and their stopping power; DOSE computes the absorbed dose from the stopping power calculated by STP. The validation process was performed in two steps. In the first one, the output of the STP code is compared to data available on NIST database; in the second one, the absorbed dose computed with DOSE is compared to the dose gathered during an experiment performed at the NASA Space Radiation Laboratory involving the bombardment of an aluminum slab with a 1 GeV proton beam. The computing model has allowed us to correlate the size of the impinging beam profile to the dose measured before and after an Al slab. The sharp increase of the dose in the position right after the slab might be due to the stochastic nature of the trajectories of charged ions in matter which makes the radiation to emerge with non-zero transverse linear momentum. From the case examined here, we conclude that aluminum is not an efficient material for Solar Particle Event shielding.
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Keywords: Space radiation; Solar Particle Events; Shielding; Geant4; Dose

1. Introduction

The risks related to space radiation exposure can be acute and deferred because of the complex nature of the space radiation environment. Acute effects are mainly associated to intense Solar Particle Events (SPE) not adequately shielded (Durante and Cucinotta, 2011). SPE are composed of about 98% of protons with energies up to several GeV and high fluences ($\approx 10^{11}$ particles/cm^2) (McGuire et al., 1986). They occur occasionally and are typically correlated to periods of maximum solar activity. Nevertheless, SPE represent the greatest danger to the unshielded crew.

The study of the interaction of protons at energies of about 1 GeV with a shielding material is very important because the main contribution to the absorbed dose is

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provided by protons emerging from the shielding material, the remaining being attributed to secondary heavy ions (≈10%) (Durante, 2002) produced after the interaction.

For the health risk assessment transport codes are typically used (Durante and Cucinotta, 2011). However, these have a high degree of uncertainty due to the fact that experimental data available for the validation of different calculation models are still scarce. The use of simulation codes is even more critical if one considers that the limits of career recommended for activities in Low Earth Orbit (LEO) by the National Council on Radiation Protection and Measurements (NCRP) are estimated by combining data from astronauts dosimeters and model calculations. The validation of models against experimental data is therefore a prerequisite for the use of any application and is highly demanded. Experimental data may be available from measurements performed on board of International Space Station (ISS) or from experiments specifically designed at accelerator labs like the NASA Space Radiation Laboratory at Brookhaven and the National Institute of Radiological Sciences in Chiba.

In this work we describe the validation process of two applications, built on the top of Geant4 package, STP and DOSE. The validation of the electromagnetic processes was performed in the range of energy characteristic of SPE (0.8–1.2 GeV); the validation of the hadronic processes was performed for protons with the energy of 1 GeV. The validation procedure of the absorbed dose calculation was in turn performed by comparing the values of the simulated dose with the ones measured during an experiment performed at the NASA Space Radiation Laboratory (NSRL), Brookhaven National Laboratory, USA (Mancusi et al., 2007; Bertucci et al., 2007).

The aim of this work is ultimately to provide a reliable tool to evaluate the effectiveness, in reducing the radiation dose for the astronauts, of materials or compounds suitable for application in space.

2. Materials and methods

2.1. Geant4

The Geant4 package includes a powerful model to simulate the passage of particles through matter. In particular, it is possible to compute observables like energy loss, range and Linear Energy Transfer (LET) (Hartmann, 1996). Moreover, Geant4 offers a large variety of utilities (Ivantchenko et al., 2014), between which the possibility to construct a detailed geometry reproducing the irradiation conditions. This characteristic feature of Geant4 has been exploited in the case presented here, namely, the interaction between a proton beam and an aluminum target.

In the design of an application, Geant4 allows users to choose among a wide range of theoretical or empirical models to describe the different physical phenomena depending on the particle type and energy range. Users are responsible for designing the physical configuration of their experimental applications. The task of optimizing it for a given experimental scenario is guided by the body of knowledge of Geant4 physics validation available in the literature (Agostinelli et al., 2003), which encompasses both validation tests of the fundamental components of Geant4 models (e.g. cross sections, stopping powers, secondary particle production, etc.) and comparisons of complex simulated observables (e.g. energy deposition patterns) with experimental measurements.

2.2. STP and DOSE applications

We have developed two applications STP (STopping Power) and DOSE. The first one implements, using Geant4 classes, the calculation of electronic energy lost into the matter. The second one calculates the mean energy imparted to matter by the ionizing radiation. For the development of these applications, six of the eight user classes provided by the kernel of the Geant4 toolkit have been implemented. In addition to the three mandatory user classes, the optional user classes have been instantiated from the abstract classes *G4UserRunAction*, *G4UserEventAction, G4UserSteppingAction* and, respectively, the concrete classes *RunAction*, *EventAction* and *SteppingAction*. The physical nature of the interaction processes are divided into two broad categories: electromagnetic and hadronic interactions. All physical processes in Geant4 involve two distinct phases: (1) the calculation and the use of the total cross section and (2) the generation of the final state.

A general view of the processes implemented in STP and DOSE is shown schematically in Fig. 1. Details of the energy range of validity and the models associated with each process are available in Physics Reference Manual (Berger et al., 2005).

2.2.1. STP

The application STP computes electronic stopping power of charged radiation in matter and was developed with the only purpose to validate the physical processes of the electromagnetic interactions category. The validation process of STP consists in comparing the outcome of the calculations with experimental data available in the literature. In particular, the NIST database PSTAR was used as reference. The results of this procedure are described in Section 3.

2.2.1.1. Experimental conditions. To validate STP against data available on NIST database, an experimental setup was defined. The incoming primary radiation is a proton beam, in vacuum, with energies from 800 MeV to 1.2 GeV. The target is the aluminum slab 7.9 cm thick (namely, 21.33 g/cm^2) typical of storm shelters used by the crew in case of emergency caused by intense SPE (Durante and Cucinotta, 2011). As described later on, the interaction of the proton beam with the thick Al target produces a cascade of secondary ions. For each of them the electronic stopping power is computed, and it is found that most of them do not emerge from the Al slab.

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