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Dosimetry in Space: The shielding effectiveness for the radioprotection of astronauts against 1 GeV protons

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Summary. — The study of materials suitable for radiation protection of astronauts in space missions is always a topic of fundamental importance. The main aim of any radiation protection program in space is to minimize the crew's exposure to ionizing radiation. This work concerns the effectiveness of shielding materials against radiation in space conditions, in particular for the Galactic Cosmic Radiation. The study was conducted by developing a simulation tool based on the Geant4 framework. The physics case reported here deals with the interaction of a 1 GeV proton beam (protons represent about 87% of the GCR flux with the energy spectrum peak around 1 GeV) with a target added with boric acid or gadolinium (Gd) to deplete neutron escaping. Charge, mass and energy distributions of secondary particles generated by the interaction are computed on the basis of different interaction models. It is found that the particles escaping the shielding material and reaching an ionization chamber located in the opposite side of the shield are still mainly protons and neutrons. The added boric acid acts as an effective neutron mitigating material. However, the average dose does not change effectively because of the additional production of alpha particles from the reaction $^{10}\mathrm{B}(\mathrm{n},\alpha)$.

1. – Introduction

The space radiation field is a mix of radiation: i) Van Allen radiation belts, ii) Galactic Cosmic Radiation (GCR) and iii) Solar Particle Events (SPEs) [1,2]. Van Allen radiation belts are formed by charged particles, in particular electrons and protons, retained by the Earth's magnetic field due to the Lorentz force. The GCR is composed of protons, α-particles and heavy ions that have baryonic components (98%) and electrons (2%). SPEs [3] occur occasionally and are typically correlated to periods of maximum solar

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(*) Corresponding author. E-mail: `filomena.loffredo@unina.it` activity. They are composed for about 98% of protons with energies up to several GeV and high fluence (10^{11} particles/cm^2).

The goal of this work is the study of the shielding effectiveness (in terms of reduction of dose to the astronauts) against GCR of some materials with particular features suitable for applications in space. The GCR represent one of the main health risk for long duration manned interplanetary missions if not adequately shielded [4] and for this reason the search of a suitable material for its shielding is always a matter of great interest.

To pursue radiation shielding on Earth there are three different approaches: to limit exposure time, to increase the distance between source and destination, and to use appropriate shields. In space the only countermeasure is shielding satisfying specific requirements, like low weight and mechanical resistance. When considering a shield, the interaction of radiation with the shield materials must be taken into account because this secondary produced radiation can also be harmful to the health of astronauts. Indeed, the presence of shielding may increase the equivalent dose [5].

In order to search for a suitable shielding material, the study of the interaction between 1 GeV protons with the absorbing material is the first important step. This work shows the numerical results of some tests performed on the Nomex [5] target treated with boric acid at different concentrations and Nomex target treated with Gd at 10% concentration. We used a transport code, developed in previous works [5, 6], to estimate the equivalent dose due to 1 GeV protons impinging on the shield. The thickness chosen for the shield is 20 g/cm^2 because such a thickness is typical of the storm shelters used by the crew in case of emergency caused by intense Solar Particle Event [1].

2. – Materials and methods

2˙1. *Geant4 STP and DOSE applications.* – The main goal of our research is to optimize the effectiveness of the shield for the radiation protection of astronauts. Since the study of the interaction between a proton beam and the target is of fundamental importance, two different applications STP and DOSE [6], based on Geant4 toolkit [7], were developed. The application STP computes the 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; instead the application DOSE has been developed to validate the physical processes belonging to the hadronic interactions category [6]. The validation process was carried out in two steps: in the first one the validation process consists in comparing the outcome of the calculations with experimental data available in the NIST database [6]; in the second one, the validation process was performed by comparing the results of the simulation with those measured during the experiment conducted at the NASA Space Radiation Laboratory (NSRL) in Brookhaven [6] involving the bombardment of an aluminum slab by 1 GeV proton beam [8, 9].

2˙2. *Target.* – The final aim of this work is to predict the effectiveness of the materials as a neutron shielding [10]. A previous study [5], on the effectiveness of shielding materials, has shown that among the various materials tested Nomex (a porous material with a percentage of air) is the best in terms of dose reduction.

In the same study, the behavior of the secondary particles contributing mostly to the dose was also highlighted. It is shown that neutrons provide the largest contribution to the dose in the case of Nomex (without air).

For this reason, it is interesting to investigate the behavior of Nomex when treated with boric acid and gadolinium. Different configurations were studied, namely, Nomex

Table I. – *Thickness and density of materials used in the space as a neutron shielding.*

Materials	Density (g/cm^3)	Thickness (cm)
Nomex	0.98	20.4
Nomex + Boric acid 10%	1.03	19.4
Nomex + Boric acid 20%	1.07	18.7
Nomex + Boric acid 30%	1.12	17.9
Nomex + Gd 10%	1.67	11.9

treated with boric acid at 10%, 20%, 30% [11] and Nomex with Gd at 10%. Since each material has a different density, the average superficial density of $20\,g/cm^2$ corresponds for each material to the thickness given in table I.

2˙3. *Setup*. – This study is a continuation of the one concerning the physics case where a 1 GeV proton beam, with a cross section (diameter) of 20 cm, bombards an aluminum slab [5] and some of the emerging radiation is captured by an ionization chamber.

The geometry implemented for the simulation is constituted by a source of 1 GeV protons beam bombarding, in air, slabs of different materials (see fig. 1). The values of each dose was computed by simulating the presence of an equivalent tissue ionization chamber ($\rho = 1.13\,g/cm^3$), of the kind produced by Cambriad by the Far West Technology, Inc. IC-17 (`http://www.fwt.com/detector/ic17ds.htm`), suspended using an aluminum support and with the center along the axis of the primary beam.

By moving the ionization chamber at different positions with respect to the slab, it is possible to compute the dose absorbed at different distances from the slab.

For each emerging radiation that has intercepted the ionization chamber, we define the event-by-event absorbed dose as the full energy carried by the radiation hitting the chamber.

In this way, once the energy spectrum of the radiation impinging on the ionization chamber is computed, the total dose can also be computed by summing the number of

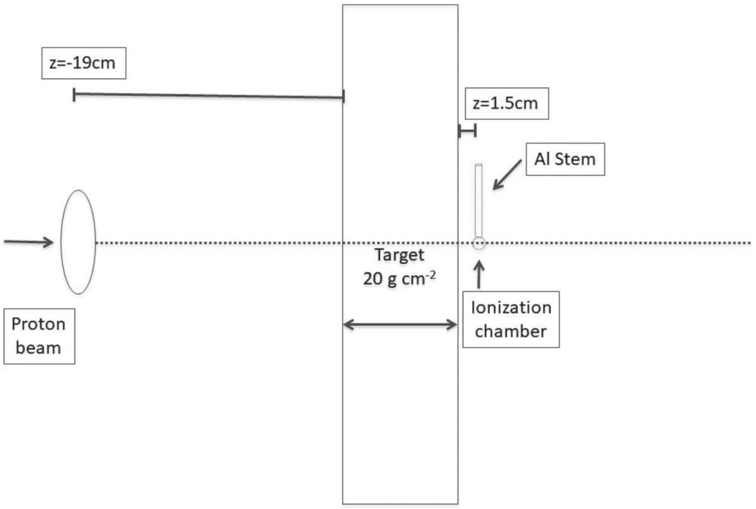

Fig. 1. – Schematic representation of the experimental setup. The figure shows the ionization chamber used for the different simulation runs. The beam cross section is 20 cm.

events in each spectral bin times the average energy of the same bin.

For each configuration (Nomex, Nomex+ boric acid 10%, 20%, 30%, Nomex+ Gd 10%) the dose is normalized to the value computed at $z = -19\,\mathrm{cm}$.

The first value of z after the target is $z = 1.5\,\mathrm{cm}$ due to the size of the ionization chamber ($\Phi = 1.12\,\mathrm{cm}$).

The width of each slab of material was chosen as to have the same average number of target atoms per cm^2, namely the same superficial density of 20 g/cm^2 usually referred to as the target thickness.

3. – Results

The first step concerns the analysis of the secondary particles produced after the interaction of the 1 GeV proton beam with a Nomex target.

Figure 2(top) shows the atomic and mass numbers distribution of the nuclei produced by the fragmentation of the target nuclei inside the shield. New nuclei, lighter than the

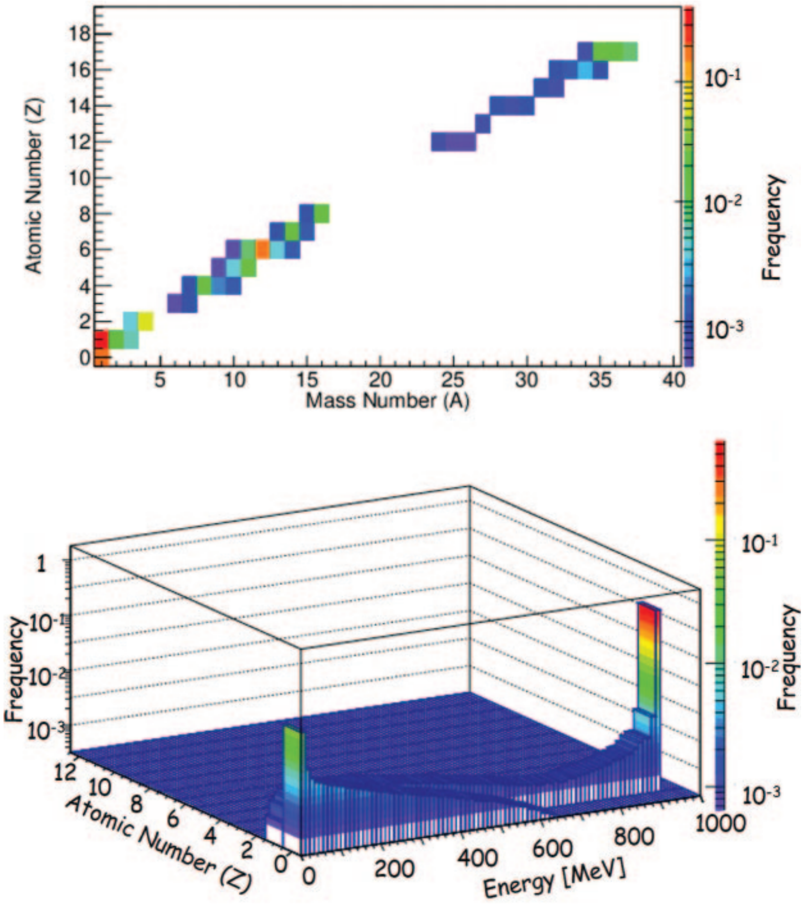

Fig. 2. – (Top) Mass and atomic numbers of the secondary particles produced in the target after the interaction between protons and Nomex material; (bottom) energy and atomic number distribution of the secondary particles that come out of the target.

heavier nuclei inside each respective target, are produced. For Nomex material, the distribution arrives up to chlorine.

Figure 2(bottom) shows that for Nomex the heaviest fragments produced are totally absorbed and shows also that only neutrons and protons give a significant contribution to the dose.

Subsequently, a more detailed analysis (see fig. 3) shows that the larger dose contribution is provided by low-energy neutrons that emerge from the target. In particular, the neutrons that escape from the target and that arrive on the ionization chamber are about 20% of the total particles.

The subsequent step is to search for a mean to hinder the escape of the produced neutrons from the target. Therefore, we considered boric acid and Gd, and evaluated, with the same code, how their addition affects the neutron transport within the shield and if a dose reduction occurs. Figure 4 and table II show the behavior of neutrons energy spectrum after the addition of boric acid (at different percentages) and Gd at 10% in Nomex.

In particular, the neutrons that escape from the target and that arrive on the ionization chamber are 7.1%, 7% and 6.8% of the total particles, respectively, for the three different configurations of Nomex with boric acid 10%, 20% and 30%. Instead the neu-

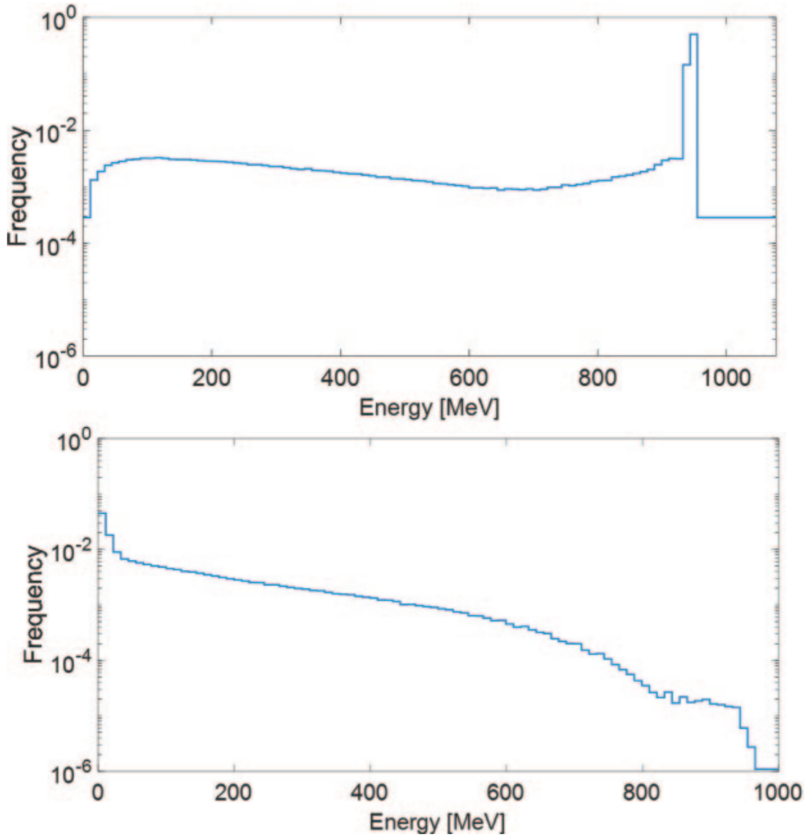

Fig. 3. – Energy spectra of protons (top) and neutrons (bottom) emerging from the Nomex shield [10].

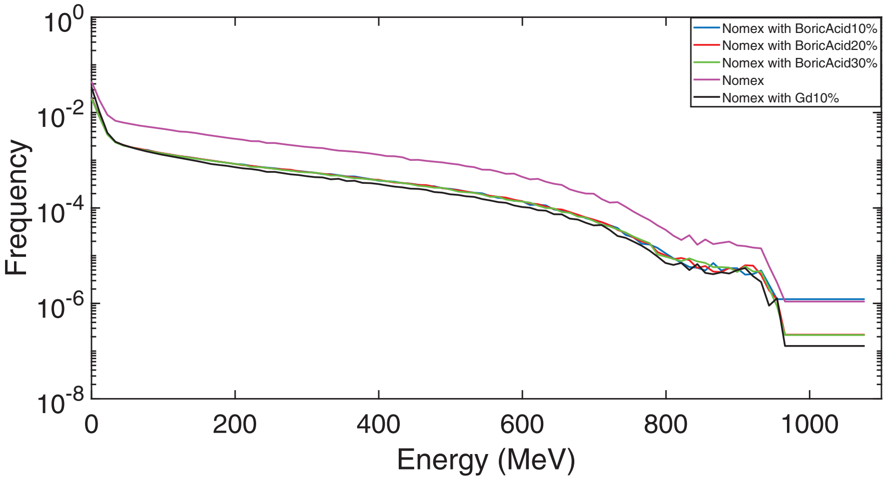

Fig. 4. – Energy distribution of neutrons particles that come out of the Nomex target without and with boric acid and Gd.

trons that escape from the target and that arrive on the ionization chamber are 8.2% of the total particles for Nomex with Gd at 10%.

Although the absorption of neutrons by boric acid is efficient, it is observed from table II that the decrease in the dose after the target does not improve consistently. In this regard, a more detailed study of the secondary particles that come out of the target shows a variation of the behavior of the protons, markedly at the lowest energies, in the different configurations with boric acid and Gd with respect to the Nomex, as shown in fig. 5.

Moreover, with respect to the Nomex, a contribution to the dose by the alpha particles is observed in the three configurations with boric acid and in the configuration with Gd, as can be seen from fig. 6.

The latter result justifies the low dose reduction after the target.

4. – Conclusion

This work suggests that a reduction of the dose may come from the suppression of low-energy neutrons. Therefore, we extended the study to cases where additional elements, characterized by larger neutron absorption cross section, such as boric acid

TABLE II. – *The percentage dose reduction.*

Materials	Dose %
Nomex [H(4%), C(54%), N(9%), O(10%) Cl((23%)]	128 ± 5
Nomex + Boric Acid 10%	126 ± 4
Nomex + Boric Acid 20%	126 ± 5
Nomex + Boric Acid 30%	122 ± 5
Nomex + Gd 10%	134 ± 7

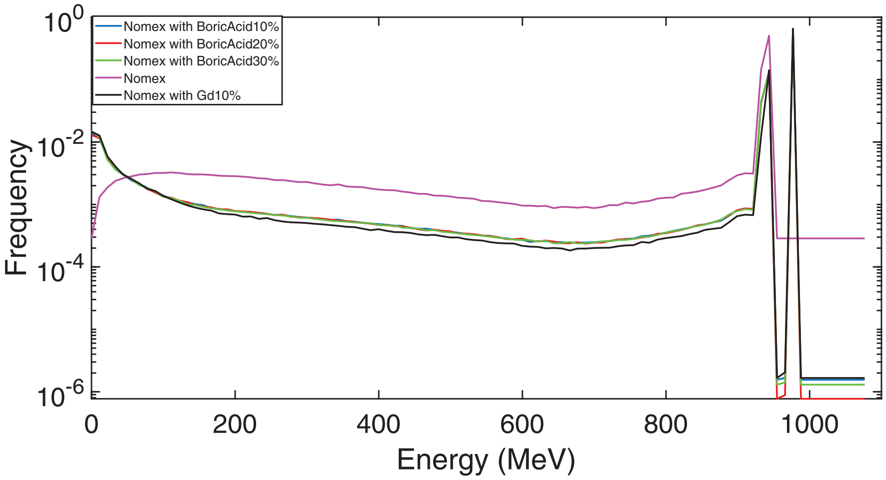

Fig. 5. – Energy distribution of protons particles that come out of the Nomex target without and with boric acid and Gd.

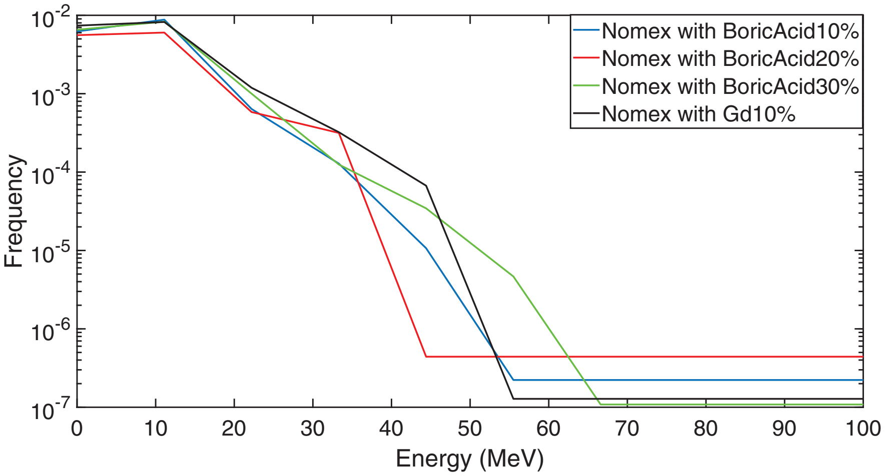

Fig. 6. – Energy distribution of alpha particles that come out of the Nomex target without and with boric acid and Gd.

and Gd, are added in small concentrations. It turned out that the added boric acid acts as an effective neutron mitigating material, as expected. However, this suppression is counteracted by the large production of alpha particles, via the $^{10}\mathrm{B}(\mathrm{n}, \alpha)$ reaction, which have enough energy to escape the shield. The additional dose due to these alpha particles counterbalance the one reduced by the neutron absorption in the same reaction, with the final overall result that the dose does not change effectively in the case of Nomex with boric acid. Finally, the best shielding performance of Nomex is achieved through the configuration with 30% of boric acid. In this latter case a dose drop of $\sim$5% has been found with respect to the Nomex without boric acid.

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