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Nomex with boron as a neutron shielding in space: Preliminary study

Filomena Loffredo([1])([2])(*), Emanuele Vardaci([1])([2]), Vincenzo Roca([1])([2]) and Mariagabriella Pugliese([1])([2])

([1]) *Dipartimento di Fisica "E. Pancini", Università di Napoli Federico II - Napoli, Italy*
([2]) *Istituto Nazionale di Fisica Nucleare, Sezione di Napoli - Napoli, Italy*

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Summary. — In this work we present a study devoted to the evaluation of the efficiency of a radiation shield, made out of the Nomex material doped with boron, in reducing the absorbed dose after bombardment with a 1 GeV proton beam. This study is relevant to the definition of optimal conditions for the shielding of astronauts from Solar Particle Events and Galactic Cosmic Radiation in space. Nomex shield is treated with boron at different concentrations. The production and transport of radiation produced after proton interaction is treated with a simulation tool based on Geant4. The added boron acts as an effective neutron mitigating material. The main preliminary result is that the average dose changes effectively despite the additional production of alpha particles from the reaction $^{10}\mathrm{B}(n,\alpha)$.

1. – Introduction

The main aim of a radiation protection program is to minimize the exposure to ionizing radiation. On the Earth, to limit the exposure to radiation there are three different countermeasures (exposure time, distance between source and target, shielding) which allow the reduction of exposure of workers and the public within acceptable limits. In space the shielding of radiation is highly problematic [1] and the only countermeasure is shielding.

The space radiation field is a mix of radiations: i) Van Allen radiation belts, ii) Galactic Cosmic Radiation (GCR) and iii) Solar Particle Events (SPE) [2]. Van Allen radiation belts are formed by charged particles, in particular electrons and protons, retained by the Earth's magnetic field. The GCR spectrum is composed of protons, He ions and heavy ions that represent the baryonic components (98%) and electrons (2%).

(*) E-mail: filomena.loffredo@unina.it

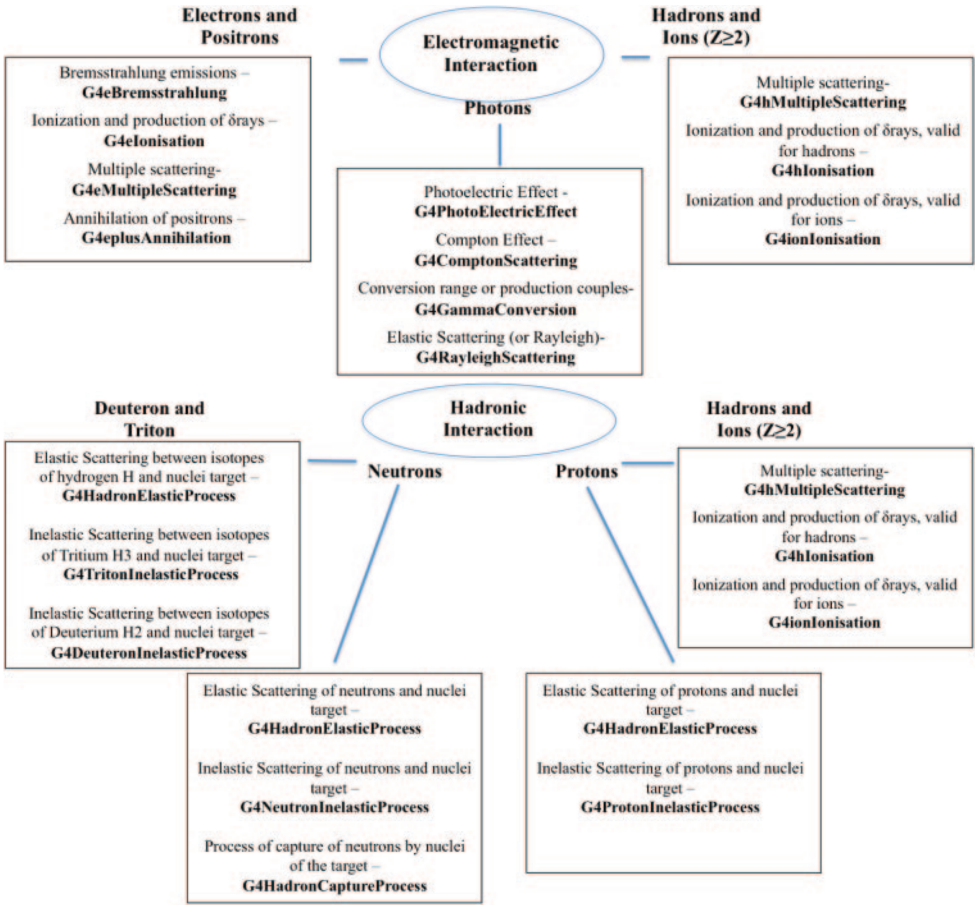

Fig. 1. – Flowchart concerning the processes implemented in STP and DOSE applications.

SPE are composed for about 98% of protons with energies up to several GeV. SPE occur occasionally and are typically correlated to periods of maximum solar activity. They represent one of the main health risk for long duration manned interplanetary missions if not adequately shielded [3] and for this reason the search of a suitable material for SPE shielding is always a matter of great interest. We focus in this work only on impinging protons with energy of 1 GeV with Nomex target for different reasons: i) protons represent about 87% of the GCR flux and the energy spectrum peaks around 1 GeV; ii) the simulated dose at 1 GeV proton energy can be verified under strict experimental conditions thus providing the benefit of the validation of the prediction capabilities of the simulation tool developed. The Nomex is an aramidic fiber composed by H (4%) C (54%) N (9%) O (10%) Cl (23%) and it is also characterized by a high mechanical resistance, which is a fundamental requirement for being used in space. This work shows the preliminary numerical results of some tests performed on the Nomex material doped with boron at different concentrations. We used a transport code, developed in previous works [4,5]. The thickness chosen for shield is 20 g/cm^2 because such a thickness is typical of the storm shelters suggested to the crew in the case of emergency caused by an intense Solar Particle Event.

2. – Materials and methods

2·1. *Geant4 toolkit.* – Geant4 is a powerful toolkit to simulate the passage of particles through matter. It includes a large variety of physics functionality for each particle type in the energy range from a few eV to several TeV. It is possible to construct a detailed geometry that reproduces the irradiation conditions. Geant4 allows users to choose among a wide range of models, driven by theory or data, or based on parameterizations to describe the different physical phenomena depending on particle type and energy range.

With respect to other general-purpose Monte Carlo systems for particle transport, Geant4 is characterized by the peculiarity of encompassing a very large variety of physics modeling options. The users are responsible for selecting the physics configuration of their experimental applications; the nature of Geant4 as a toolkit prevents the definition of any "default" physics configuration. The task of optimizing the physics configuration for a given experimental scenario is guided by the body of knowledge of Geant4 physics validation available in the literature [6], 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.* – The aim of our research program is the comparison among the responses, in terms of dose, of different configurations of Nomex boron-added material after the interaction with radiations. In particular the interaction between a proton beam and different targets conducted with two applications, STP and DOSE, based on the Geant4 toolkit, was studied [5]. The applications STP and DOSE work in pipeline. STP generates the secondary radiation after hadronic and electromagnetic interactions, and DOSE computes the stopping power and the dose relative to the radiation emerging from the shield. The validation process was carried out in two steps. In the first one, the output of the STP code is compared to data available on the National Institute of Standards and Technology (NIST) database; in the second one, the computed absorbed dose is compared to the one gathered during an experiment performed at the NASA Space Radiation Laboratory involving the bombardment of an aluminum slab by a 1 GeV proton beam [5, 7, 8]. The same set of applications has been used in this study for the different configurations of Nomex material. The flowchart (see fig. 1) shows the large wealth of interactions that are included in the physical model which describes the interaction of a particle with matter and fig. 2 shows the experimental setup.

2·3. *Target and setup.* – A previous study concerning the effectiveness of different materials, in terms of dose reduction, has shown that among the various materials tested Nomex, with a percentage of air, is the most efficient. In the same study, the behavior of the secondary particles contributing 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) [9]. The final aim of this work is to test the effectiveness of some additional chemical element as a neutron shielding.

For this reason it is interesting to investigate the behavior of Nomex with different percentages of boron. Three different configurations were studied, namely, Nomex treated with boron at 10%, 20%, 30%. Since each material has a different density, the thickness of $20\,\mathrm{g/cm^2}$ corresponds for each material to the width given in table I.

The geometry implemented for the simulation is constituted by a source of 1 GeV proton beam bombarding, in air, slabs of different configurations of Nomex material

TABLE I. – *Thickness and density of materials that can be used in the space as a neutron shielding.*

Materials	Density (g/cm^3)	Slab width z (cm)
Nomex	0.98	20.4
Nomex (90%)+B (10%)	1.12	17.9
Nomex (80%)+B (20%)	1.26	15.9
Nomex (70%)+B (30%)	1.40	14.3

(see fig. 2). The values of each dose were computed by simulating the presence of an equivalent tissue ionization chamber ($\rho = 1.13\,\mathrm{g/cm^3}$), 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.

This equivalent tissue ionization chamber is the one that was used in the experiment described in [7, 8], and was already implemented in the simulation tools as described in [4, 5]. 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. The dose is normalized to the value computed at $z = -19\,\mathrm{cm}$.

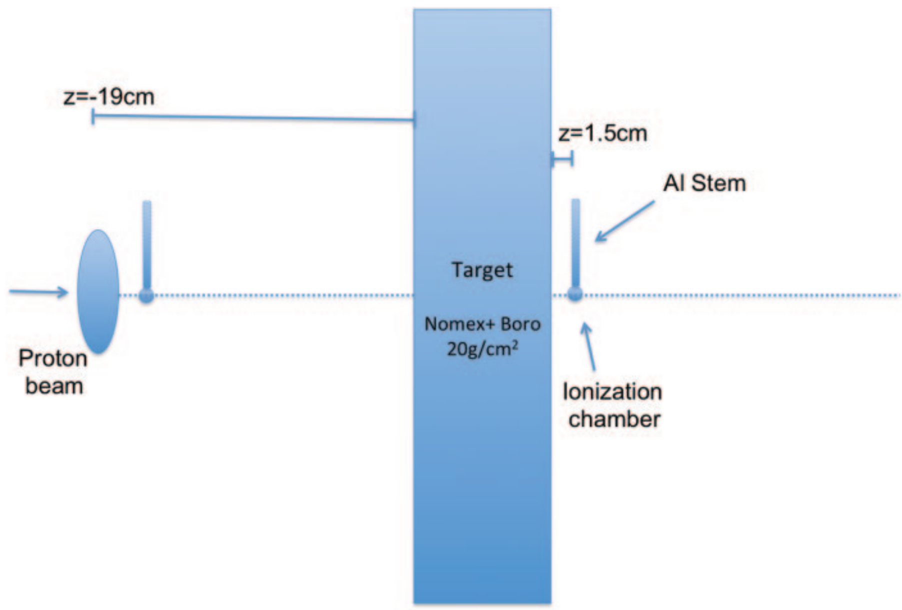

Fig. 2. – Schematic representation of the experimental setup. The figure shows some of the different positions of the ionization chamber used for the different simulation runs. The beam cross-section is 20 cm.

TABLE II. – *The percentage dose reduction.*

Materials	Dose (%)
Nomex	128 ± 5
Nomex (90%)+B (10%)	110 ± 3
Nomex (80%)+B (20%)	118 ± 2
Nomex (70%)+B (30%)	117 ± 5

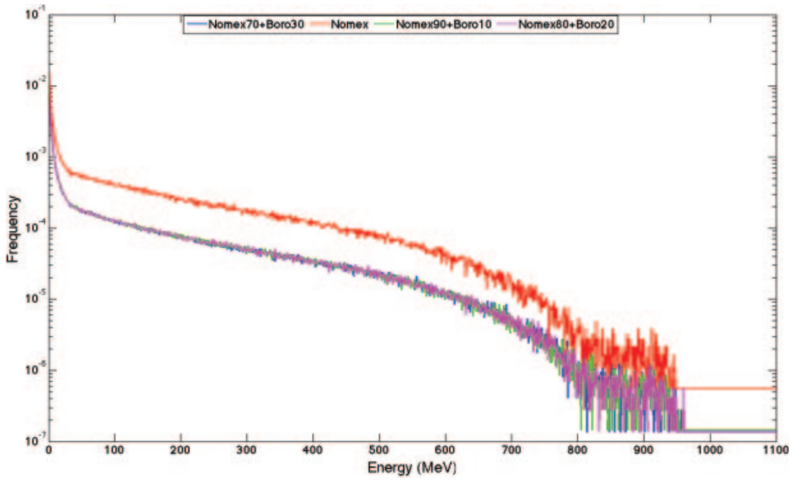

Fig. 3. – Energy distribution of neutrons that come out of the Nomex target without and with different percentage of boron.

The value after the target is $z = 1.5\,\text{cm}$ due to the size of the ionization chamber ($\Phi = 1.12\,\text{cm}$). The width of each slab of material was chosen so as to have the same average number of target atoms per cm^2, namely the same superficial density of $20\,\text{g/cm}^2$ usually referred to as the target thickness.

3. – Results

The first step concerns the analysis of the neutrons that come out of the Nomex target without and with boron after the interaction of 1 GeV proton beam with the target (see fig. 3).

In particular, the neutrons that escape from the target and that arrive on the ionization chamber are $\cong 7\%$ of the total particles, for the three different configurations of Nomex with boron 10%, 20% and 30%. Table II shows the dose values for different configurations of Nomex with and without boron, which are normalized to the value simulated without shielding. After the Nomex target there is a dose increase equal to 28% compared to the value in $z = -19\,\text{cm}$ (fig. 2). Furthermore, this increase is reduced in the presence of the Nomex target with addition of boron (10%, 20%, 30%) respectively to the value 10%, 18%, 17%. With respect to the Nomex without boron these values

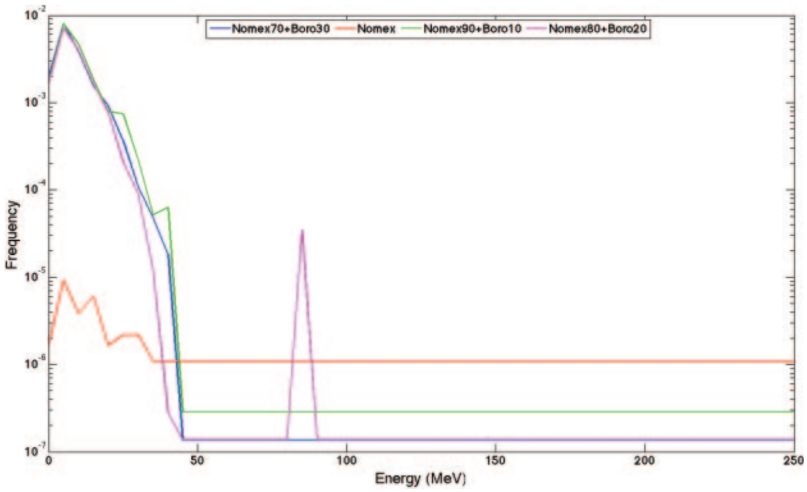

Fig. 4. – Energy distribution of the alpha particles that come out of the Nomex target without and with different percentage boron.

correspond to a dose drop of ∼14%, ∼8% and ∼9%, respectively.

Despite the large production of alpha particles due to the reaction ^{10}B (n, α) (see fig. 4), the absorption of neutrons by boron is efficient. This can be observed from table II where the decrease in the dose after the target is shown.

4. – Conclusion

This study was inspired by the need to reduce the dose due to the abundant production of low-energy neutrons in the interaction of a 1 GeV proton beam with the Nomex shield. We considered Nomex material with the addition of boron, being boron characterized by a relatively large neutron absorption cross-section. As expected, boron acts as an effective neutron mitigating material despite the large production of alpha particles via the ^{10}B(n, α) reaction. The main preliminary result is that the dose drops effectively in the case of Nomex with boron. The best shielding performance of Nomex is achieved through the configuration with 10% of boron. In this latter case there has been found a dose drop of ∼14% with respect to the Nomex without boron.

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