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Effects of multilayer and multimaterial structures on space proton radiation protection

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ABSTRACT

An investigation of multilayer (and multimaterial) structures for space proton radiation protection is presented. In this research, both the role of the material itself on the shielding efficiency and the effect of the structure of the shield were considered. By using simulations with the software package Geant4, the shielding efficiencies for high energy protons were calculated for three different materials (aluminum, copper and tantalum) and for two multilayer structures. It was found that the optimum solar proton protection is obtained with a multilayer structure. In order to prove the validity of simulation results, 9 MeV proton irradiation experiments were performed. The good agreement between simulation results and experimental data confirms that the Geant4 code can be used to accurately calculate high-energy proton radiation protection.

1. Introduction

Space radiation environment consists of charged particles, such as Van Allen radiation belts and galactic cosmic rays, resulting in harmful effects on materials used in spacecraft [1–11]. The lower energy charged particles are easily attenuated by the shielding material. However, the secondary particles produced by the higher energy particles in shielding materials need to be taken into account for spacecraft [3,12,13]. The secondary particles, such as protons, neutrons, pions, deuterons, alphas are the products of the spallation reaction, which can be induced by high-energy protons and other types of cosmic rays, and can lead to the ionizing and displacement damage to materials used in spacecraft [14,15].

Various materials and structures can give different shielding efficiency to high-energy charged particles in space. There have been lots of studies on this subject using various simulation tools available, such as MCNPX, Geant4, Fluka and so on. However, few of these investigated the relative fluxes of the secondary particles produced by high-energy protons in various shielding materials. Especially, most of the references are only based on the simulation results, and there are no experimental data to prove the validity of simulation results [16–18].

A better material and structure, for shielding space high-energy protons, is to be researched by simulation and measurement methods in this study. Geant4 is a Monte Carlo simulation package used in a number of high energy physics experiments; it is used in many smaller size experiments and projects in a variety of application domains [19]. Therefore, Geant4 was chosen to simulate and calculate the optimized shielding materials and structure in this study. In order to prove the validity of simulation results calculated by Geant4, 9 MeV protons irradiation tests were performed.

The mission was defined as long-term radiation effects in space GEO orbit. Thus, only the solar proton environment was considered as an input in this study. Other types of particles are not important in assessing the long term radiation effects in space because of their low fluxes (e.g., the solar heavy ions, or galactic cosmic rays) or low energies (e.g., trapped protons) [20].

2. Solar proton environment

Large solar events are correlated with the eleven-year solar cycle, and are much more probable or frequent during solar maximum than during solar minimum. These events are not predictable, except on a statistical basis. The time profiles of solar event particles generally show a rapid rise (a few hours or less), followed by a slow decay (several hours to several days). The flux is approximately isotropic during the decay phase. Different events have different shapes (spectral shapes) and sizes, but the very large event that occurred in August 1972 is often used as a reference [21,22]. A more recent event in October 1989 produced a similar proton spectrum [23], which encourages us to continue to use the August 1972 event as a reference.

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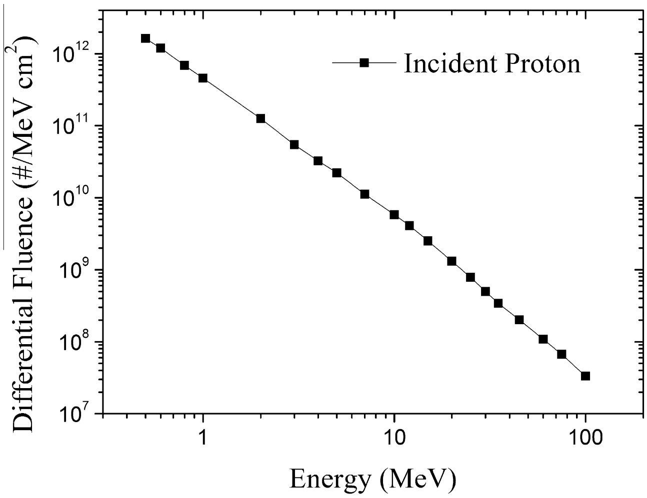

Fig. 1. The solar proton energy spectrum in GEO orbit.

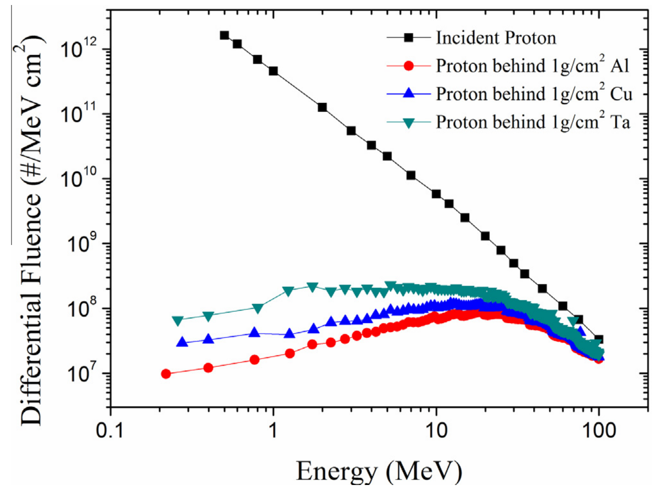

Fig. 2. Proton energy spectra after 1 g/cm^2 aluminum, copper and tantalum shield.

Solar event protons can give contribution to ionizing damage, displacement damage, and single event effects. Given that an event occurs (even if it is not particularly large), the solar event protons are the primary contributions to ionizing and displacement damage for spacecraft in interplanetary space. Also, the relative abundance of protons to heavy ions are large enough to compensate for the small cross section for producing single event effects by indirect ionization, so solar event protons can be an important contribution to single event effects in proton-susceptible devices [24,25]. Therefore, it is significant to find a material or structure, which has ideal shielding capability to solar event protons (high-energy protons).

The NASA model for emission of solar protons (JPL-91) [26] was considered as representative solar proton environments. For the solar proton model, the seven active-year total-proton differential fluence with a 95% confidence level was used as input. The spectra for solar protons environments in GEO orbit are shown in Fig. 1. In this figure, the mission duration time is 10 years. It is clear that the proton differential fluence reduces with increasing the energy.

3. Calculated results

High-energy protons as shown in Fig. 1 are potential candidates that can lead to nuclear reactions, resulting in secondary particles. These secondary particles significantly affect the accurate assessment of the radiation effects, which include, but are not limited to, secondary protons, neutrons, electrons, gamma rays, etc. In this section, based on the differential fluence in Fig. 1, emerging protons, neutrons, electrons and gamma rays behind 1 g/cm^2 shielding materials accumulated over 10 years were given to show the shielding capabilities of various materials, while the energy spectra of these particles behind shielding structures with a thickness of 1.5 mm accumulated over 10 years were plotted to characterize the shielding capabilities of different structures.

Shielding materials are tantalum (ρ = 16.65 g/cm^3) regarded as a "heavy" material, copper (ρ = 8.96 g/cm^3) as a "middle" material and aluminum (ρ = 2.70 g/cm^3) as a "light" material. The target (or detector) material is silicon (Si). The Shielding structure is a mono or multilayer solid sphere with a point silicon detector at the center.

3.1. Influence of materials

Figs. 2–5 give the differential energy spectra of the emerging protons, neutrons, electrons, and gamma rays behind 1 g/cm^2 tan-

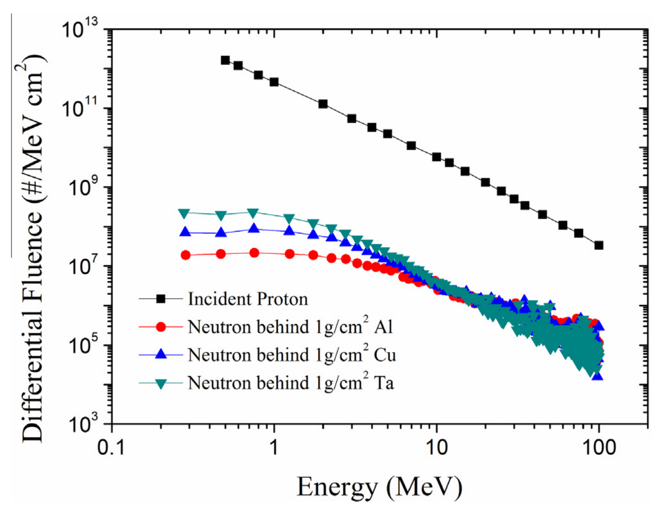

Fig. 3. Energy spectra of neutrons produced by protons after 1 g/cm^2 aluminum, copper and tantalum shield.

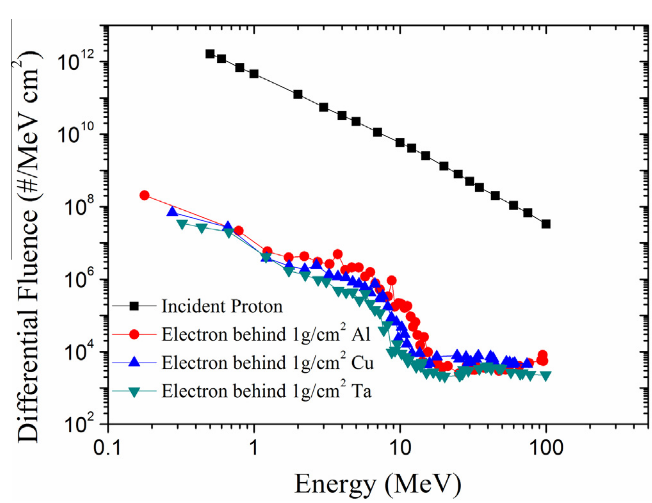

Fig. 4. Energy spectra of the electrons produced by protons after 1 g/cm^2 aluminum, copper and tantalum shield.