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Space neutron spectrometer design with SSPM-based instrumentation

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ABSTRACT

The compact, robust nature of the CMOS solid-state photomultiplier (SSPM) allows the creation of small, low-power scintillation-based radiation measurement devices. Monitoring space radiation including solar protons and secondary neutrons generated from high-energy protons impinging on spacecraft is required to determine the dose to astronauts. Small size and highly integrated design are desired to minimize consumption of payload resources.

RMD is developing prototype radiation measurement and personal dosimeter devices using emerging scintillation materials coupled to CMOS SSPM's for multiple applications. Spectroscopic measurements of high-energy protons and gamma-rays using tissue-equivalent, inorganic scintillators coupled to SSPM devices demonstrate the ability of an SSPM device to monitor the dose from proton and heavy ion particles, providing real time feedback to astronauts. Measurement of the dose from secondary neutrons introduces additional challenges due to the need to discriminate neutrons from other particle types and to accurately determine their energy deposition. We present strategies for measuring neutron signatures and assessing neutron dose including simulations of relevant environments and detector materials.

1. Introduction

Astronauts are exposed to ionizing radiation from a variety of sources, including galactic cosmic rays, solar energetic particles, and particles trapped in Earth's magnetosphere. This initial study has focused on galactic cosmic rays (GCR), consisting primarily of high energy protons, which efficiently produce secondary neutrons by spallation with the spacecraft. Other sources and specific operational environments will be treated in future works. A calculated GCR proton spectrum in the vicinity of Earth is shown in Fig. 1 [1,2], along with the calculated solar energetic proton spectrum for a large, neutron-producing event. The GCR spectrum below about 1 GeV is modulated by solar activity and varies with the solar cycle. A spectrum representative of the average is shown in Fig. 1.

1.1. Simulated spacecraft environment

The MCNPX code was used to determine the expected flux of particles from galactic cosmic ray proton interactions with spacecraft material [9]. A spherical aluminum shell with a thickness of 10 cm is used as a mock spacecraft, and the flux in Fig. 1 is used to generate the flux of neutrons, protons, and gamma-rays inside the spacecraft. The simulation environment is a spherical aluminum shell of thickness 10 cm as in Fig. 2. A 5 cm shell was also simulated to study the shielding dependence of the particle flux; these results are not shown. The calculated flux inside the spacecraft is shown in Fig. 3.

The rate of proton events (Fig. 3) indicates that a space dose measurement for neutrons will require strong discrimination between proton and neutron events. This is especially true since both particles create a similar response in the organic scintillator, which is the central high-energy neutron detector in the proposed apparatus. The proposed design shown in Fig. 4 uses scintillation segments read out by an SSPM. Segments are collectively contained within a plastic scintillation shield, which is also read out by an SSPM. In this design, charged particles that deposit energy in the plastic scintillator are rejected by anti-coincidence requirement in the main detector. Low-energy gamma-rays can be rejected by pulse height or pulse shape discrimination; high-energy gammas are rejected when Compton scattered electrons trigger the anti-coincidence shield (ACS). Since the mean free path of an electron in organic material is nearly 1 cm at 2 MeV, the Compton scattered electron will have a high probability of escape above 2 MeV.

The ability of the SSPM coupled to a plastic scintillator instrument to detect protons has been demonstrated using the charged particle dosimeter shown in Fig. 5 [3]. This instrument consists of a 3 mm SSPM coupled to a 3 mm plastic scintillator cube. This device has been exposed to protons and heavier charged particles at the NSRL facility in Brookhaven NY and the HIMAC facility in Chiba, Japan.

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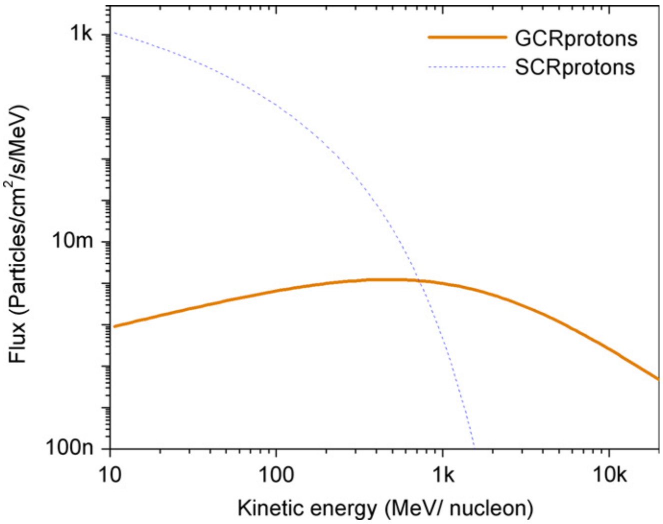

Fig. 1. The energy distribution of cosmic ray protons in the vicinity of Earth. Solar cosmic rays (SCR) were modeled as protons with an exponential distribution in rigidity (momentum per unit charge, with units of MV). The spectral parameter (Φ_{SCR}=100 MV) and number of protons greater than 30 MeV (about 6000 protons/cm^2/s) was selected to model large solar energetic particle events with energies sufficient to produce neutrons (for example, similar to the 23 February 1956 and 4 August 1972 events). The galactic cosmic rays were distributed in energy according to the functional form used by Castagnoli and Lal [1], which they adapted from the work of Masarik and Reedy [2]. The proton spectrum representative of the average (Φ_{GCR}=550 MV) is shown.

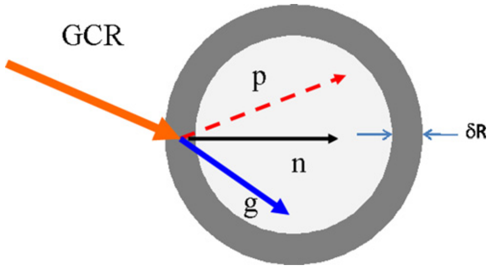

Fig. 2. Galactic cosmic rays create secondary particles including neutrons (n), protons (p), and gamma rays (γ), which are scattered into the spacecraft, which was simulated as a spherical shell of thickness delta *R*.

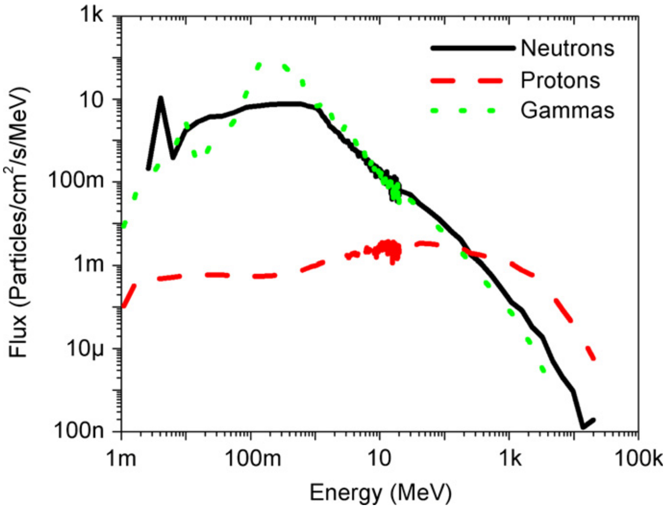

Fig. 3. Calculated secondary particle flux inside 10 cm Al shell using the GCR background as the incident field.

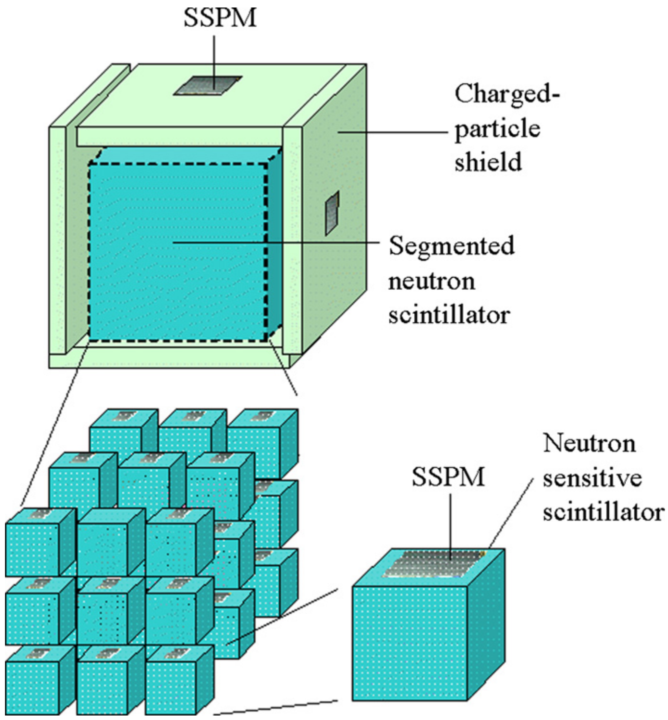

Fig. 4. Conceptual design of the detector system. Each minor segment consists of an SSPM coupled to an organic scintillator. Several of these segments are coupled together to increase the total detector volume and allow the potential for tracking of multiple scatter events.

Fig. 5. Photograph of charged particle dosimeter module on a business card to provide scale. The module contains a battery, power supply circuitry, amplifier, a peak hold circuit and a microprocessor, which digitizes and stores the pulse heights. A USB connection provides battery connection and data readout.

2. Materials and methods

2.1. CMOS SSPM

Two SSPM designs were used in this work. A 3 mm × 3 mm SSPM with 2024 pixels is used in the device shown in Fig. 5, which provided the measurements in Fig. 6 and shows the ability to do proton discrimination. A 1 cm × 1 cm SSPM device with approximately 51k pixels, shown in a photograph in Fig. 7, was used in neutron scintillator measurements that are shown in Fig. 8. Both SSPM devices are fabricated in a standard commercially available CMOS process and they have a detection range from 400 to 900 nm with peak quantum efficiency at 475 nm. The SSPM consists of an array of single photon sensitive avalanche photodiodes connected