Investigating Bio-mimetic Origami Radiation Shield Design Geometries for Mitigating Transient Soft Errors Induced by Cosmic Rays in Solid-State Storage Devices

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Contents

§1 Abstract

This research investigates the impact of radiation exposure from hadrons of terrestrial cosmic rays (primarily neutron, proton, and pion) on solid-state storage devices, specifically focusing on the transient effects that cause single event upsets (SEUs) or soft errors. The experiment involves measuring soft-error rates of a commercially available solid-state storage device controlled by NodeMCU micro-controller when exposed to hadron beams from the T9 PS accelerator that simulate terrestrial cosmic radiation exposure. In particular, we propose to test the shielding efficacy of different origami geometric radiation shield designs, bio-mimetically inspired by the cellular structure of radiation resistant Melanized fungi. The proposed experiment draws on two strands of previous studies – radiation induced soft errors in solid state devices, and geometric cellular structure of radiation-resistant fungi in shielding. The results of this study will potentially contribute to the development of new bio-mimetic origami geometric design philosophies and principles for radiation shield designs.

§1.1 Why we chose to participate in BL4S

We chose to participate in the Beamline for Schools competition (BL4S) because it provides a unique opportunity to conduct research at CERN, one of the world's premier research institutions. The PS T9 beam facility is perhaps a handful of experimental facilities around the world, where our proposed experiment can be conducted. As students interested in physics and engineering, we are excited to have the chance to work with this particle accelerator facility, an opportunity to elevate a high-school experiment idea to the level of real scientists, and contribute to ongoing research efforts in the field. We believe that participating in BL4S will provide us with a valuable learning experience and help to prepare us for future academic and professional pursuits.

§1.2 Motivation for this proposal

The increasing reliance on solid-state storage devices in high radiation environments, such as outer space, makes it crucial to understand the effects of radiation on these devices. While high radiation flux may lead to permanent damage to the exposed micro-chip, at lower flux-levels, ionising radiation causes arbitrary switching of *data bits* stored on the micro-chip. Such radiation-induced transient errors, also known as Single Event Upsets (SEUs) or Soft Errors [Ziegler et al., 1996], leads to unpredictable system behaviour or worse system failure in critical equipment like communication satellites, exposed to ionizing radiation from cosmic rays at higher altitudes. Figure 1 shows the process of a single bit flip induced by ionising radiation in a transistor gate of a solid-state storage device. Figure 2 shows the incidence of cosmic ray induced hadron radiation on critical equipment at different altitudes. Table 1 shows the observed composition of hadron particle ration observed at sea-level and at the altitude of 32,000 ft. Therefore, it is necessary to investigate the susceptibility of these devices to radiation and evaluate the effectiveness of radiation shielding methods.

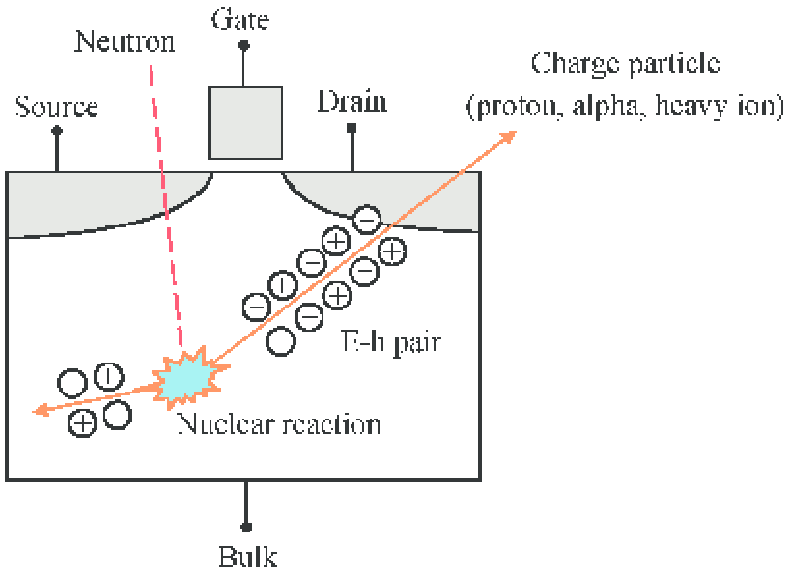
This research proposal aims to contribute to the understanding of the impact of neutron, proton, and pion radiation, principle hadrons of terrestrial cosmic rays [Ziegler et al., 1998], on transient soft-errors induced in solid-state storage devices. In particular we plan to explore the efficacy of innovative geometric configurations of physical radiation shields, such as origami designs inspired by radiation-resistant fungi [Vasileiou and Summerer, 2020]. The study has the potential to inform the development of novel geometric principles for radiation shield design for use in high radiation environments, including space exploration [Duzellier, 2005].

Table 1: Principle Hadrons of Terrestrial Cosmic Rays

Altitude	Neutrons	Pions	Protons
Sea-level	94%	3%	3%
32,000 ft	52%	36%	12%

Source:[Ziegler et al., 1998]

Figure 1: The radiation induced charged particle causing a single bit to flip in a microchip transistor gate



Source: [Zhao et al., 2015]

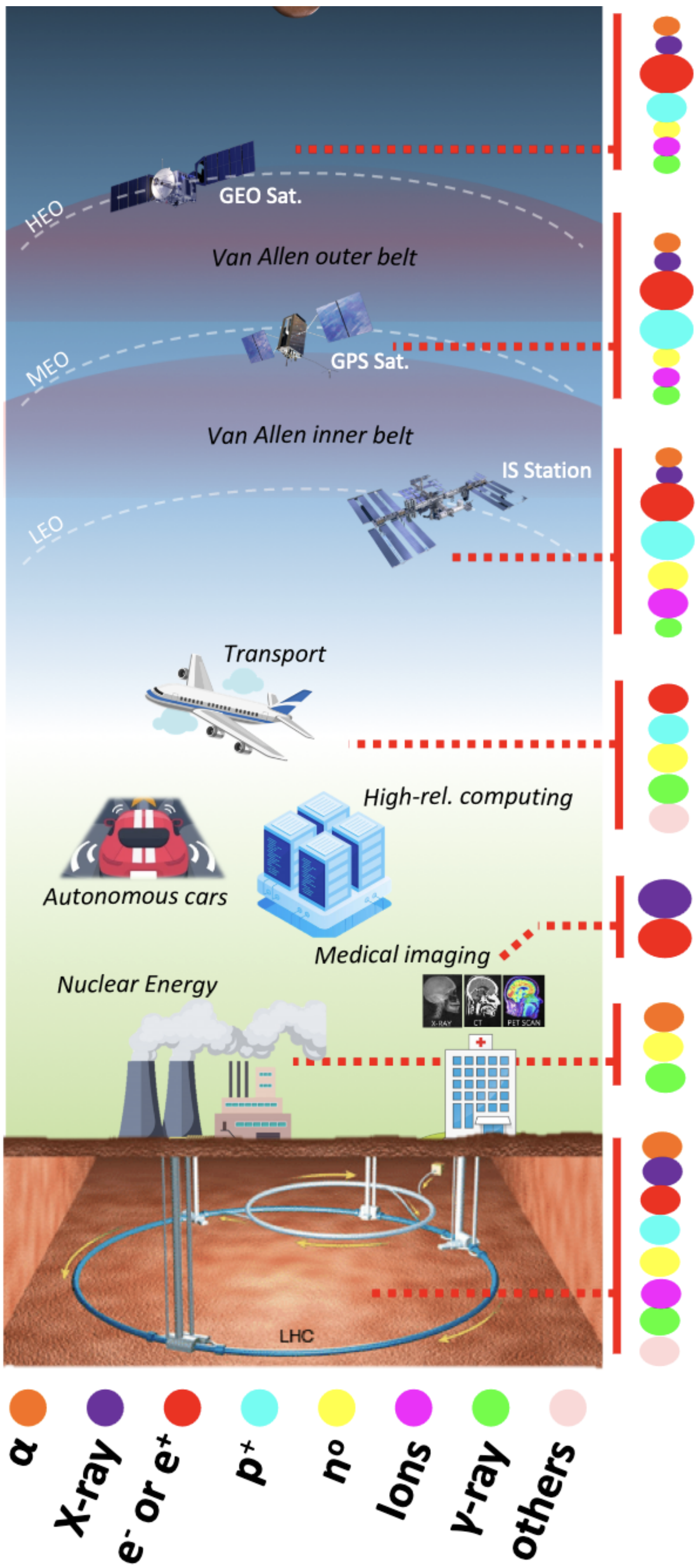
§1.3 What we hope to gain from this experience

As students participating in BL4S, we hope to gain valuable hands-on experience in conducting scientific research at a world-class facility like CERN. We aim to deepen our understanding of the geometric design of radiation shields and its effects on solid-state storage devices. We hope to learn about the practical aspects of experimental design, data collection, and analysis. We also look forward to collaborating with experts in the field and learning from their knowledge and expertise.

We aspire to make a meaningful contribution to the scientific community and potentially impact the development of radiation-resistant technologies for use in high radiation environments, which could have real-world applications in fields such as space exploration and beyond.

Overall, we see this experience as an opportunity for personal and academic growth, and we are excited to learn, explore, and contribute to the scientific community through our research conducted at CERN as part of the BL4S program.

Figure 2: Incidence of cosmic radiation and particle composition at various altitudes



Incidence of cosmic radiation at various altitudes coming from galactic events such as supernova explosions and pulsars that emit γ-ray and high energy particles (83.3% p+, 13.72% α, 2% β, 0.98% heavy ions) (source:[Prinzie et al., 2021])

§2 Literature Review

A series of experiments conducted at IBM, during the period 1978-1994, showed that exposure to ionizing radiation can cause both permanent and *transient* impact on silicon based VLSI[1] Our proposed idea for the experiment borrows from the extensive study of radiation induced soft error in different type of solid-state microchips conducted by [Ziegler et al., 1996]. We also attempt to conduct multiple read-write operations in-sync with the beamline pulse to measure the soft-error rates, inspired by the much more sophisticated work of [Iwashita et al., 2020].

§2.1 Bio-mimetic Geometry of Radiation Shields

One approach that has been investigated to mitigate the damaging effects of radiation on electronic devices is the use of biomimetic material geometry for shielding of sensitive components. In a study conducted by Vasileiou and Summerer in 2020 [Vasileiou and Summerer, 2020], melanized fungi found thriving in high radiation environments (e.g. the Chernobyl disaster site [Zhdanova et al., 2004, Dadachova and Casadevall, 2008]) were used as a basis for developing a radiation shielding material. Melanin, a pigment found in these fungi, was found to exhibit some effectiveness in shielding against radiation, with higher levels of melanization resulting in increased protection. However, the study also highlighted the importance of the structure of the biological shield itself. When the mimicked structure of the melanized fungi was exposed to radiation, the shielding effectiveness was significantly reduced, indicating that the shape and structure of the material play a crucial role in its shielding mechanism.

Figure 3: The study suggests that the shape of the melanized fungi plays a significant role in the shielding mechanism.

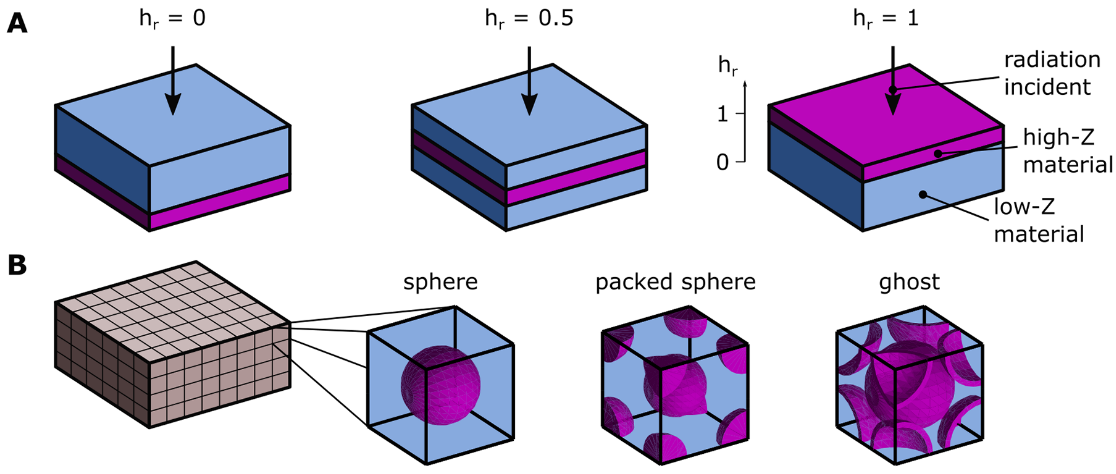


Image source: [Vasileiou and Summerer, 2020]

[1]Very large-scale integration (VLSI) micro-chips consists of millions or billions of transistors in a single chip. Today almost all microprocessor and memory chips used in various electronics devices are VLSI devices [Wikipedia, 2023].

§2.2 Origami-inspired Radiation Shields for Solid State Storage

Origami-inspired designs offer promise for creating effective radiation shields for electronic devices in harsh environments. Studies have shown that origami bellows with high compressibility and resilience to environmental conditions could be a viable alternative to metal bellows for space applications [Butler et al., 2016]. Additionally, origami-inspired surfaces can be used to control radiative properties in thermal management systems [Mulford et al., 2015]. Leveraging biological fungi-inspired origami designs could lead to innovative solutions for mitigating radiation damage on solid state storage devices. Further research in this area could pave the way for effective origami-inspired radiation shields for electronic devices.

§3 Methodology and Experimental Design

§3.1 Equipment

For the proposed research, we will make use of the following equipment.

1. NodeMCU [NodeMcu,]
2. 8GB SD Card
3. Proton beam source (from the PS accelerator)
4. Scintillator for beam tuning and particle composition detection.
5. Origami shielding designs (using melanin-inspired materials [Vasileiou and Summerer, 2020], hollow micro-spheres)
6. Computer (for data analysis)

§3.2 Feasable Melanized Materials

Some feasable melanized materials included but are not limited to:

- Eumelanin nanoparticles
- Carbonized melanin (i.e., melanin that has been heated to high temperatures to form a carbonaceous material)

§3.3 Methodology

To conduct our experiment, we will use a NodeMCU microcontroller and a standard SD card. The NodeMCU will be programmed to collect data from the SD card in synchronisation with the beam pulse cycle from the PS accelerator. The NodeMCU program will compute soft-error rates by checking and counting for all bit-flips from the batch read-write operations.

§3.4 Transient Effects and Radiation Damage Mitigation

In this experiment, we will specifically focus on transient effects of radiation on the SD card, without causing permanent damage. The secondary beams available at the PS accelerator include particles with energies ranging from 0.2 to 15 GeV. These high-energy particles can potentially cause permanent damage to the SD card, leading to data loss or corruption. Therefore, it is essential to mitigate the radiation damage and ensure that the SD card remains functional after exposure to radiation.

§3.5 Experimental Design

We will use origami shielding designs inspired by melanized fungi to shield the SD card from radiation exposure. We will experiment with different designs using various materials such as hollow micro-spheres and other melanin-inspired materials [Vasileiou and Summerer, 2020]. We will expose the shielding designs and the SD card to the proton beam from the PS accelerator, and record the error rate of the SD card before and after exposure. The error rate will be measured by the NodeMCU using the pseudo-code shown in 3.1. This is a less sophisticated synchronization method when compared with [Iwashita et al., 2020] (which uses Time of Arrival based synchronization to measure continuous bit-flip rates). However, our setup but will suffice to measure bit-flips in batches timed with radiation exposure cycles from the PS T9 beam.

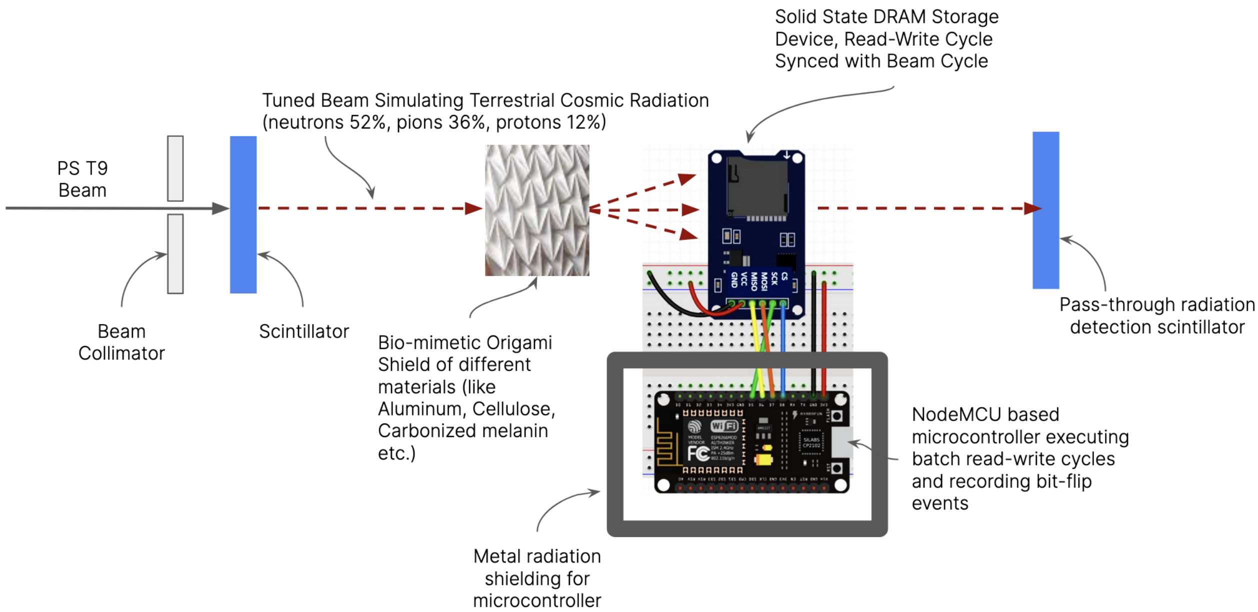


Figure 4: Schematic of the proposed experiment

§3.5.1 NodeMCU Psuedo-Code

We propose the following pseudo-code to program the NodeMCU to collect data for error rates.

Algorithm 3.1 —

```
Require: NodeMCU, SD card
Ensure: Error rate measurement results
function MEASURE_ERRORS
    Initialize SD card
    Open file for writing
    for i ← 1 to n do
        Write random data to SD card
        Read data from SD card
        if read data is not the same as written data then
            Increment error count
        end if
    end for
    Calculate error rate
    Write error rate to file
    Close file
    return error rate
end function
```

§3.5.2 Control Group

Indeed, we repeat this experiment without the shield to ensure that there is no interference or error rate changes solely due to other factors such as experimental conditions or variability in the proton beam. This control group will serve as a baseline for comparison with the shielded groups.

§3.6 Possible Shielding Models

We will explore origami-inspired shielding designs that use melanin-inspired materials and hollow micro-spheres [NodeMcu,]. One potential design is based on the close-packing of equal spheres, as described by Wikipedia [Wiki, 2022]. This design involves folding a sheet of paper into a series of connected triangular pleats, creating a three-dimensional structure that can be filled with hollow micro-spheres.

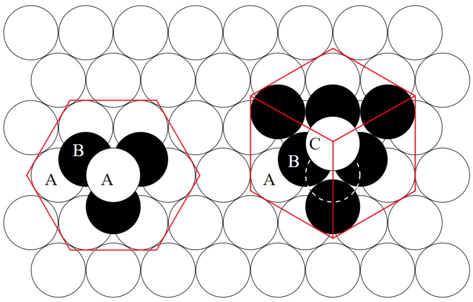


Figure 5: Close-packing of equal spheres [Wiki, 2022].

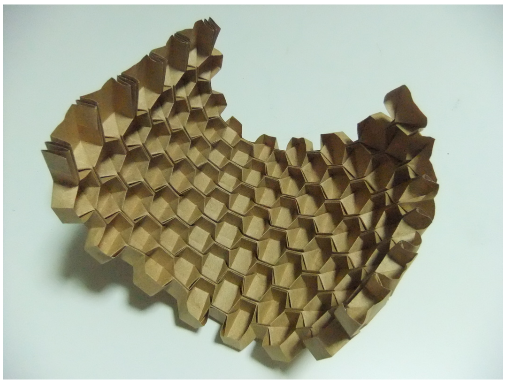


Figure 6: A sphere-folding pattern by Hern-Cheng [Cheng,].

As described in [Vasileiou and Summerer, 2020], when recreated using a melanized material with the packed structure should provide effective shielding against ionizing radiation.

§3.6.1 Other Possible Shielding Models

In addition to the close-packing of equal spheres design, there are other origami-inspired shielding models that could potentially work for our experiment. Two such designs are the Miura-ori and the Waterbomb base patterns, as shown in Figure 7 and Figure 8 respectively.

The Miura-ori pattern, developed by Koryo Miura [Georgakopoulos et al., 2021], is a tessellated pattern that can fold and unfold in a compact and rigid manner. This pattern has been used in various applications, including solar panels and deployable space structures. The Waterbomb base, developed by Robert J. Lang [Fonseca and Savi, 2021], is a simple yet versatile base pattern that can be used to create complex three-dimensional structures.

These origami-inspired designs can be created using melanin-inspired materials and hollow micro-spheres, similar to the close-packing of equal spheres design mentioned earlier [Vasileiou and Summerer, 2020]. These structures may provide effective shielding against ionizing radiation due to their intricate folding patterns and three-dimensional configurations.

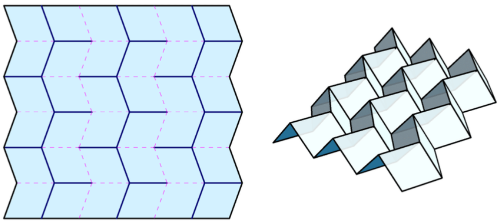


Figure 7: Miura-ori folding pattern. Image source: [Georgakopoulos et al., 2021].

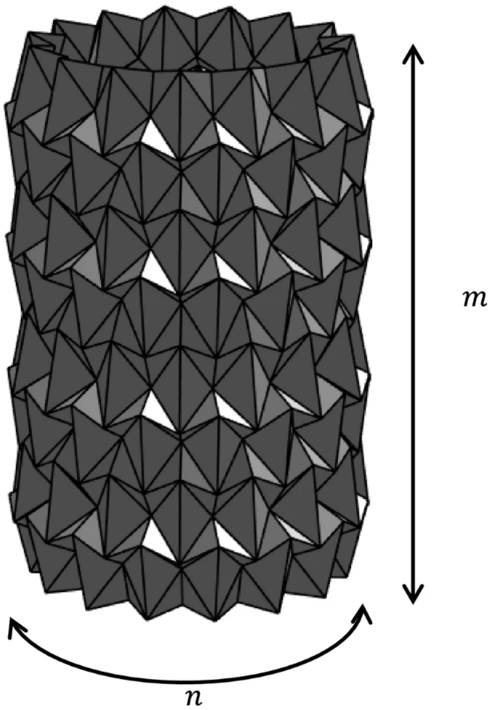


Figure 8: Waterbomb base folding pattern. Image source: [Fonseca and Savi, 2021].

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