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The Effects of 0.4 to 10 GeV/c Muons on M.2 Solid State Drives

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We propose an experiment that will investigate the effects of muons on an M.2 solid state drive through bit-flips, as a way to study the impact of sea-level cosmic rays on electronics.

INTRODUCTION

From the 2003 Belgian election to the 2009 Toyota recall, the effects of bit flips (also known as single-event upsets (SEU)) caused by cosmic rays have been known to affect computers. SEU have become more frequent by consequence of Moore's Law approaching its physical limit. Additionally, Solar Cycle 25 is predicted to peak during mid-2025 [1], namely the number and intensity of solar flares and coronal mass ejections, two major sources of Earth-bound, high-energy particles, will increase [2]. As such, modern technology's situation is precarious; electronics are more susceptible to cosmic rays than ever before. The proposed experiment will focus in particular on the effects of muons on modern storage in computers.

FRAMEWORK

The objective of this experiment is to study the effects of cosmic rays on modern electronics. To do so, an M.2 SSD, analogous in many respects to the storage of other modern electronics, will be subjected to a beam of muons equivalent to the cosmic rays that reach Earth's sea level. Muons are fundamental particles that are classified, like electrons, as leptons and are sometimes referred to as μ-leptons. Like the other charged leptons, muons do not interact with nuclei through the strong force, but rather electromagnetically, via photons, or with the weak interaction, via W or Z bosons. Muons are charged particles that are 207 times heavier [3] than the electron and they have a mean lifetime of 2.197 μs [4]. In addition, muons with energies ranging between 0.4 to 10 GeV/c [5] can travel through the Earth's atmosphere and reach sea level with a flux of 1 muon/cm^2·s [6].

Muons can be created by the rapid decay of pions emerging from the collisions between high-energy baryons and the nuclei of atoms in the upper atmosphere [7]. This process can be replicated with the T9 beam at CERN by bombarding a beryllium plate with high-speed protons. Many of their decay patterns lead to the production of unstable, intermediary hadrons that, in turn, form negative pions which will eventually yield negative muons [8]:

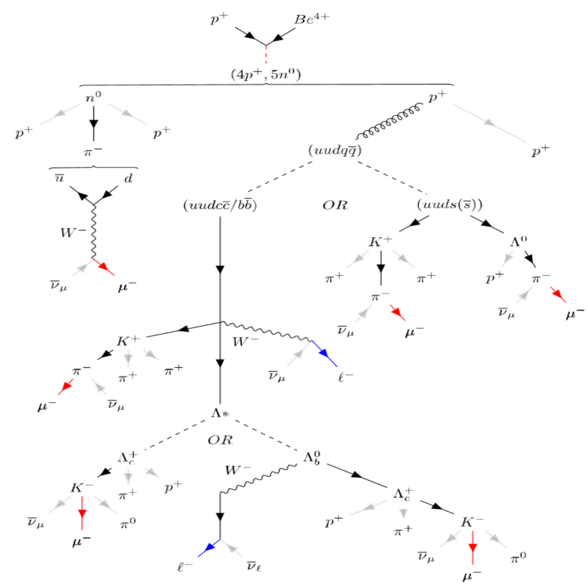

FIG. 1. Sample Decay Modes yielding muons (red) and leptons (blue) following an accelerated proton collision with a beryllium nucleus.

$$p^+ + Be \rightarrow X + \pi^\pm \tag{1}$$

Isolating the muons is essential to the experiment because failing to do so would result in the presence of more than one independent variable. If this were to be the case, it would be impossible to categorically attribute any single-event disturbances in the M.2 SSD to the muons with which it interacted. Such exposure will favour muon capture by the PCB molecules of the storage devices. These ionized free radicals are susceptible to crosslinking: the formation of new unsaturated bonds, and ultimately the modification of its molecular lattice structure [9]. This will allow for observation of the extent to which muons may corrupt the storage, processing, and memory systems of today's technology [10].

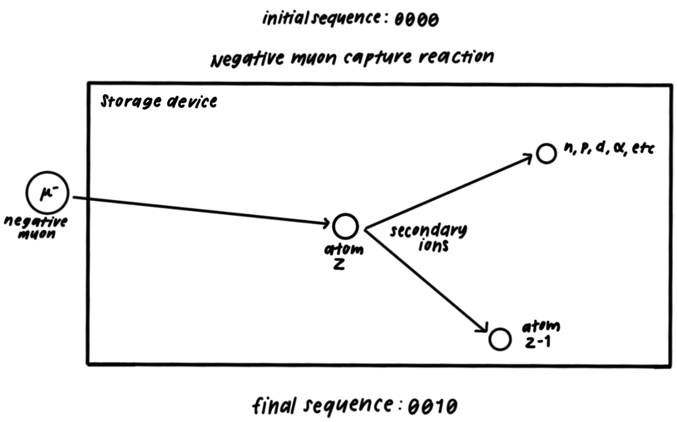

FIG. 2. Negatively-charged muon capture process within a storage device.

Innovations in nanotechnology made as recently as 2021 have seen the creation of 2-nm wide nanochips [11]. Despite increasing performance and energy efficiency of electronics, this engineering feat comes at the cost of susceptibility to SEU. Therefore, subjecting an M.2 SSD to a focused and controlled beam of muons will serve as a fantastic microcosm for the effects of cosmic rays on modern devices. The muon beam will likely induce SEU via the significant modifications to their molecular structure, with results similar to the aforementioned cases. Consequently, there would be an expected increase in corrupted storage data.

EXPERIMENTAL SETUP

In the proposed experiment, three separate trials will be conducted - each in triplicate - consistent with the reported momentum range of the muons that reach sea level to further understand their ionizing effect on the M.2 SSD. The momenta of muons chosen lie at the poles of the range, 0.4 GeV/c & 10 GeV/c, and an average value of these two figures, 5.2 GeV/c.

Initially, a beam composed entirely of protons at an energy of up to 26 GeV will collide with a beryllium plate, which will result in a secondary beam made up of lighter subatomic particles on which experimentation can be done. Kaons (mean lifetime: 12 ns [12]) and lambda baryons (lifetime: between 0.2 and 263 ps [13]), among other particles, are present in this resulting beam and will quickly decay into negatively-charged pions (lifetime: approximately 26 ns [14]). It is at this point that equipment can be used to isolate the resulting muons from the beam's other constituent subatomic particles.

First, the beam resulting from the collision will pass through an iron filter (80 cm x 50 cm x 50 cm)[15], separating the muons from the heavier subatomic particles, namely hadrons. Then, dipole electromagnets will be used to select for a beam consisting solely of negative particles. In addition, their quadrupole counterparts can be used to adjust the focus of the beam. After that, a first collimator will be placed to attenuate its momentum and a second will be used to reduce its halo [16]. Cherenkov detectors, tuned accordingly, will be used to confirm that the beam consists solely of muons and scintillator counters could provide further information regarding the number of particles that will interact with the M.2 SSD. Finally, the refined beam of muons will collide with the M.2 SSD, inducing varying degrees of SEU, which will be noted upon data collection.

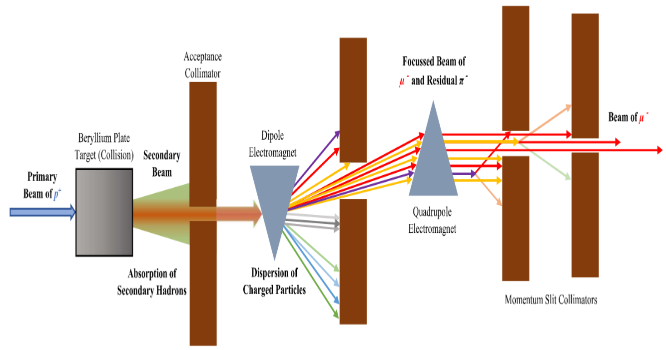

FIG. 3. Setup inside the T9 beam experimental area. Hadron products are blocked by an iron acceptance filter, and muons are isolated via dipole electromagnets after charged pion decay.

CONCLUSION

Building on the findings from this research, it would be fascinating to monitor CPU and memory aging and usage. This would require a Linux based system monitoring tool like *nmon* to view their effects. With the development of increasingly large data servers containing information pertinent to the livelihood of the global population, it is imperative that data corruption due to cosmic rays be studied extensively in the upcoming years, prior to the solar maximum of Cycle 25. In addition to the benefits our research will bring to the world of computing, our proposal demonstrates the capacity of high-energy particle physics to solve issues on a global scale while exposing larger arrays of audiences to the science, and hopefully encourages further research on the interactions between cosmic rays and modern electronic devices. Sharing our passion with the world and working with CERN would be our greatest privilege.

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