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A proposal to study long-lived isotopes produced by thermal neutron irradiation of digital devices

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Abstract. In this work, we present a facility to study errors in digital devices exposed to thermal neutrons from a beam hole in the IEA-R1 nuclear reactor, as well as the long-lived isotopes produced in the irradiation of digital electronic devices under a slow neutron field. Preliminary results obtained with the analysis of a 28nm SRAM-based Xilinx Zynq-7000 FPGA are presented.

1. Introduction

Exposure of digital devices to radiation may induce several types of effects. Directly ionizing radiation will deposit charge within the system, while indirectly ionizing radiation will, by interaction with the device's material, produce directly ionizing radiation.

While the effects of photons, heavy ions, electrons and fast neutrons have been thoroughly studied [1, 2], studies on the influence of slow neutrons are scarce. These neutrons have kinetic energies around 0.02 eV, thus they are unable to break chemical bounds or even to excite individual electrons, so they will produce directly ionizing radiation only by means of nuclear reactions. The most common reactions for low-energy neutrons are $^{10}\text{B}(n, \alpha)^7\text{Li}$ and the neutron capture (n, γ) reactions, with considerably large cross sections ($\sigma > 1b$) for most metals and rare-earth elements. These capture reactions, in turn, will frequently produce radioactive nuclides that will emit delayed directly ionizing radiation (either β^- or β^+), aside from rendering the system radioactive.

Recently, new ultra-high-current accelerators have been proposed (e.g., the *NUMEN* accelerator in Italy [3]) that should create strong ($10^5 \text{cm}^{-2} \cdot \text{s}^{-1}$) slow neutron fields in the positions where nuclear instrumentation must reside, thus requiring the study of the effect of such neutron fluxes in data acquisition digital systems.

In this work, we have studied the built-up radioactivity in a Xilinx Zynq-7000 FPGA board subjected to neutron irradiation in beam holes of a nuclear reactor.

2. Induced Radioactivity

In the case of exposure of N nuclides of a given type to a particle flux of ϕ ($\text{cm}^{-2} \cdot \text{s}^{-1}$), the rate at which a given nuclear reaction with a cross section σ happens is given by:



$$\frac{dN}{dt} = N \cdot \sigma \cdot \phi \quad (1)$$

If the produced nuclide is radioactive and decays with a half-life $T_{1/2}$, the activity of these nuclides (A^*) present in the sample after an irradiation period t will not be a linear function of t :

$$A^* = N \cdot \sigma \cdot \phi (1 - e^{-\lambda \cdot t}) \quad (2)$$

where $\lambda = \ln(2)/T_{1/2}$. This means that for irradiation times up to a single half-life the growth is approximately linear, while after 7-10 half-lives the activity saturates at $N \cdot \sigma \cdot \phi$. Therefore, for a device that should star under irradiation for a long period of time (up to several years), the build-up of long-lived radionuclides ($T_{1/2} > 100$ days, for instance) could present a real issue, both in terms of radiological protection and for the integrity of the device itself. Moreover, for these long-lived radionuclides, the activity build-up can be simulated by increasing the irradiation flux, as when $t \ll T_{1/2}$, $(1 - e^{-\lambda \cdot t}) \approx t$.

3. Experimental Procedure

In a preliminary test to check for signals of activity build-up in digital acquisition systems, a 28nm SRAM-based Xilinx Zynq-7000 FPGA board was irradiated in the IEA-R1 nuclear reactor. As the test also intended to check the suitability of the available facilities for this type of test, irradiations were performed in distinct beam-holes in the IEA-R1 reactor.

Initially, the board was irradiated in the monochromatic low-energy facility installed in beam-hole number 6, where the neutron flux is $\sim 6 \times 10^4 \text{ cm}^{-2} \cdot \text{s}^{-1}$ for two 8-hour periods (as the reactor operates on an 8 hour per day basis, these irradiations were carried out for two consecutive days). Then, in order to check the suitability of the other facility, in the next day the board was irradiated in beam-hole number 3, under a mixed neutron field (mostly thermal, but epithermal and fast neutrons are also present); during this test the reactor's operational power was progressively raised so that, in the last hour, the flux reached approximately $10^8 \text{ cm}^{-2} \cdot \text{s}^{-1}$.

The residual radioactivity was then studied by gamma spectrometry, both after 18h of the end of irradiation and after 6 days of decay. These measurements were performed using an Ortec HPGe detector, with the spectra analysed using Canberras Genie-2000 software. A rough efficiency calibration was performed using point sources ($^{166\text{m}}\text{Ho}$ and ^{152}Eu) placed at approximately the same distance as the board – an exact calibration was not possible for these tests, as the board is very heterogenous and the exact position where each nuclide was produced cannot be determined.

4. Preliminary Results and Discussion

In the first measurement, after 18 h of decay, the total gamma activity was estimated to be around 30 kBq. The strongest individual contribution came from the annihilation peak at 511 keV (~ 6 kBq), followed by noticeable contributions (~ 0.5 kBq) from ^{198}Au ($T_{1/2} = 65$ h), ^{82}Br ($T_{1/2} = 35$ h), ^{64}Cu ($T_{1/2} = 13$ h) and ^{24}Na ($T_{1/2} = 15$ h). All of the identified radionuclides have half-lives below 3 days and shouldn't present relevant issues.

In the second measurement, after 6 days of decay, total gamma activity was estimated around 5 kBq, with noticeable contributions (~ 500 Bq) from the annihilation peak and also from ^{198}Au ($T_{1/2} = 65$ h), ^{82}Br ($T_{1/2} = 35$ h), and ^{64}Cu ($T_{1/2} = 13$ h), all of which have half-lives short enough to be considered irrelevant in long-term exposition studies. Minor relevant contributions (~ 5 Bq), though, were noticed for the activation of ^{60}Co ($T_{1/2} = 1925$ days), ^{182}Ta ($T_{1/2} = 115$ days), ^{65}Zn ($T_{1/2} = 244$ days) and ^{124}Sb ($T_{1/2} = 60$ days) – these radionuclides have

longer half-lives and, specially in the cases of ^{65}Zn and ^{60}Co , may present really relevant issues if the board is to be irradiated for a period of time of several years.

5. Conclusions

Both facilities tested in this work proved to be suitable for the irradiation of electronic devices. The results of the preliminary tests showed that at least some long-lived nuclides – most noticeably ^{60}Co and ^{65}Zn – were produced during these tests, emphasizing the importance of further studies. A shortcoming noticed in these studies resides in the definition of a reasonable gamma-detection efficiency value, which will only be possible by splitting the board in its individual components or by using restrictive collimators during irradiation or counting. Nevertheless, if the aim of the study is simply to assess the production of isotopes that may pose a safety threat after long irradiations, the large uncertainties that would come from the gamma-counting efficiency should not be a problem.

References

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