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Neutrons for studies of radiation hardness

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Summary. — This paper discusses the neutron irradiations for radiation hardness assurance tests by focusing on high-energy physics applications. Neutron sources commonly used for the testing of electronic components and materials are spallation neutron sources and nuclear reactors. The production of neutrons with two-body reactions is a viable alternative to standard sources as it allows different configurations of neutron spectra among which mono-energetic neutrons, of particular interest for the study of the neutron damage as a function of the energy.

1. – Radiation hardness

Radiation affects the correct operation of materials and electronics. Critical environments such as the space, nuclear reactors and facilities for high-energy physics (HEP) experiments are a hazard for the design of sensitive components. Electronics and materials for such applications are tested at radiation facilities with the aim of reproducing as close as possible the conditions at which the device will be used or, in more effective way, of simulating the effects induced by radiation [1-4]. Electronic devices experience different types of damage depending both on the characteristics of the incident radiation (type, energy, dose and dose rate) and on those of the device. Total Ionizing Dose (TID), Displacement Damage (DD) and Single Event Effect (SEE) are the three categories of effects considered on electronic systems [5]. TID and DD cause progressive degradation of the performances of the device, while SEE, mainly dependent on the Linear Energy Transfer (LET) of the incident radiation, can be even destructive in the worst case. Radiation types such as electrons, X- and gamma-rays mainly interact by ionization with the atoms of the device which in turn lead to malfunction. Although the long-term degradation effects of electronic devices due to TID are similar to that of

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TABLE I. – *Neutron-induced reactions on silicon and oxygen.*

Reaction	$E_{t,{}^{28}\mathrm{Si}}$ (MeV)	$E_{t,{}^{16}\mathrm{O}}$ (MeV)
Elastic	0	0
Inelastic	1.78	6.06
(n,α)	2.76	2.35
(n,p)	4.00	10.24
(n,d)	9.70	10.52
(n,n+α)	10.35	7.61

DD, the physical mechanisms are different. The incident radiation can locally displace the atoms from their original sites in the crystalline lattice by modifying the material structure and by affecting devices' fundamental properties. Protons, heavy ions (also referred to as HZE ions) and neutrons induce DD in electronic components. SEEs are short-term effects caused by interaction of a single energetic particle with an electronic device. The incident radiation generates localized ionization paths which induce SEEs if the charge delivered is greater than a threshold. The charge collected by the device can produce a spurious voltage signal on a sensitive node which leads to malfunction in the electronic circuit. High-energy charged particles, mainly HZE ions, induce SEEs in electronic systems; SEE probability increases with the increasing LET of the incident radiation.

2. – Neutron damage

Neutrons are a serious thread for the correct operation of electronic devices. Owing to the peculiarity of their interaction with matter (neutrons interact with atomic nuclei only), neutrons mainly induce DD and SEEs in electronic systems. The damage is due to secondary charged particles produced by the interaction of neutrons with the atoms of the lattice. The contribution to TID is generally negligible. The reactions induced by neutrons on silicon and oxygen (which are the main elements in the electronics) include the scattering and production of light charged particles.

These reactions, summarized in table I, have energy threshold E_t starting from about 2 MeV. Nevertheless, failures in semiconductor devices due to thermal neutrons have been observed for those devices fabricated with boron traces, such as the borophosphosilicate glasses (BPSGs) [6]. The isotope ^{10}B (20% natural abundance) has high probability of absorbing a thermal neutron. The cross section of the ^{10}B(n,α)^{7}Li reaction is 3837 barn at 0.0253 eV while that of the ^{10}B(n,tot) is 3840 barn (at the same energy). As a result, SEEs in components with boron are mainly due to short range alpha particles. The failure of electronic components induced by neutrons is a concern for the equipment used in environments such as nuclear reactors, facilities for HEP experiments, space and atmosphere (both high altitude and sea level).

2·1. *Neutrons in high-energy physics.* – Experimental apparatuses used in HEP are exposed to high radiation levels of which neutrons are a significant part. As an example, the outer tracker of the Compact Muon Solenoid (CMS) at CERN is exposed (during Phase 1) to an maximum fluence of 10^{14} neq/cm^2. The equivalent neutron fluence (neq/cm^2) is used to express the neutral particle contribution to the overall radiation

TABLE II. – *Q-values and threshold energies of the reactions used for the production of mono- and quasi–mono-energetic neutrons.*

Reaction	Q-value (MeV)	E_t (MeV)
D(d,n)^{3}He	3.3	0
T(p,n)^{3}He	17.6	0
T(p,n)^{3}He	−0.8	1.0
^{7}Li(p,n)^{7}Be	−1.6	1.8

environment. The 1 MeV equivalent neutron fluence is the fluence of 1 MeV neutrons that produce a damage in a material equivalent to that produced by an arbitrary fluence with a specific energy distribution. The neutron fluence spectrum expected during the CMS Phase-2 High-Luminosity Large Hadron Collider (HL-LHC) extends up to 10 GeV with a fluence peak of 10^{15} neq/cm^2 at 1 MeV. The neutron fluxes expected for the HL-LHC operation range from 10^3 cm^{-2}s^{-1} with a maximum of 10^6cm^{-2}s^{-1} in the muon endcap ME0.

3. – Neutron sources for the testing of materials

The operation of electronic devices and materials for applications in harsh radiation environments is tested at radiation facilities. One approach to the device's testing consists in reproducing as close as possible the actual radiation environment at which the device will be exposed. The tests are always "accelerated", namely the flux of the testing radiation is higher, by several orders of magnitude, than the flux of the actual radiation. With regards to the facilities for neutron testing, spallation-based neutron sources provide atmospheric-like neutron spectra with fluxes up to 10^6 cm^{-2}s^{-1}. For example, the Los Alamos Neutron Science Center (LANSCE) has both high-energy and low-energy neutron sources for semiconductor testing with an accelerated factor of 10^7. The corresponding atmospheric-like neutron spectrum spans over a wide range from hundreds of keV to 800 MeV. European neutron sources for the device's testing for aerospace and ground applications such as the ISIS Rutherford Appleton Laboratory (RAL) at Oxford (UK) and ANITA neutron beam facility at Uppsala (SE) provide atmospheric-like spectra with fluxes of 10^6 cm^{-2}s^{-1}. Nuclear reactors deliver neutrons with continuous energy spectra and high neutron fluxes. As an example, the IBR-2 reactor at Dubna (RU), recently proposed as a facility for radiation hardness test of materials, delivers fast neutron fluxes of 10^{12} cm^{-2}s^{-1} by reaching (in 11 days irradiation) an integrated fluence of 10^{18}cm^{-2} over an area of $16 \times 16\,\text{mm}^2$. The corresponding gamma contamination level reaches 60 kSv/hr. In this regard, the study of the damage with mono-energetic radiation is considered as a viable alternative to the testing with a continuous spectrum with high gamma background.

3·1. *Neutron production with particle accelerators.* – A powerful method to produce mono- and quasi–mono-energetic neutrons with charged particle accelerators is with two-body reactions [7]. The characteristics of four reactions commonly used for this purpose, are summarized in table II.

The reactions with triton are the most convenient in terms of neutron production cross section and in particular in inverse kinematics. However, the sources using the triton

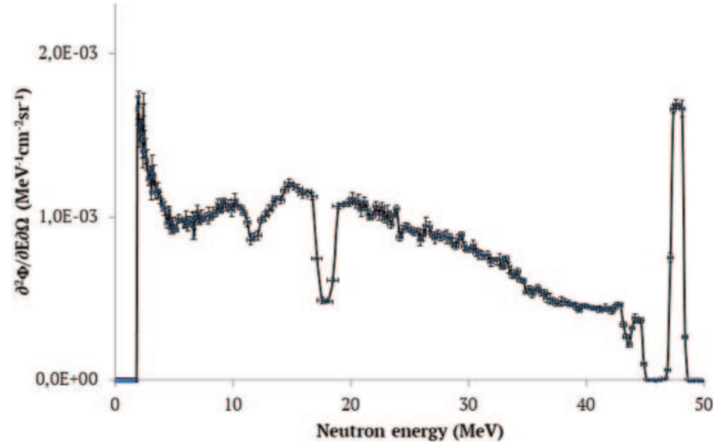

Fig. 1. – FLUKA neutron spectrum of 50 MeV protons lithium of 2 mm.

as both the target or the beam pose problems related to the triton's radioactivity. The Frascati Neutron Generator (FNG), for example, uses triton as target for the production of 14 MeV neutrons with a rate of 10^{11} neutrons/s. In addition, it uses a deuterium source for the production of 2.5 MeV neutrons. The most of particle accelerators for mono-energetic neutron production are mainly based on D(d,n)^{3}He and ^{7}Li(p,n)^{7}Be reactions. With regard to the latter, this reaction has several advantages. Since the ^{7}Li is a stable (92.5%) isotope, the manufacturing of a lithium target is relatively easy. The residual nucleus produced in the reaction (^{7}Be) is radioactive (53 d) with emission of a 478 keV gamma ray. The post-irradiation gamma ray spectrometry of the lithium target allows measurements of the production yield of mono-energetic peak neutrons. In addition, the modulation of the lithium target and beam energy allows a different configuration of neutron spectra. A continuous neutron spectrum (up to the incident beam energy) can be produced by means of an "infinite thickness", namely a thickness greater than the range of protons in lithium. A quasi–mono-energetic neutron spectrum can be made with a reduced thickness at higher energy. As an example, fig. 1 shows a FLUKA simulation of the neutron spectrum obtained by interaction of a 50 MeV proton beam with a 2 mm lithium target.

The single peak at 48 MeV is from the ^{7}Li(p,n)^{7}Be reaction. The remaining part of the spectrum is from ^{7}Li(p,n)^{7}Be* reactions that leave the residual nucleus ^{7}Be* in its excited states and from all reactions other than the binary channel. One of these reaction is the three-body break-up reaction ^{7}Li(p,n^{3}He)^{4}He with a relatively high cross-section and low-energy threshold ($E_t = 3.7$ MeV). The simulated neutron yield is 10^5 neutrons/ (cm$^2 \cdot$ s $\cdot$ nA).

4. – Discussion

The harsh environment of HEP experiments poses serious problems of radiation hardness to the materials and electronics employed. The high radiation levels of today HEP experiments will be exceeded by about one order of magnitude with the upcoming experiments of HL-LHC. The study of the radiation damage with neutron beams has a twofold advantage. Firstly, neutrons significantly contribute to the complex radiation field of HEP experiments. Secondarily, neutrons induce SEEs ad DD in electronic components with a negligible TID contribution, by allowing a factorization of the effects. Standard tests are performed at facilities providing atmospheric-like neutron spectra at typical rates ($10^6\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$) of accelerated tests for aerospace and ground applications; in addition, nuclear reactors are used as high-intensity neutron sources providing continuous spectra with high gamma contamination level. An alternative to the testing with continuous spectra is with mono- and quasi–mono-energetic neutrons. Among the two-body reactions for neutron production, the ^{7}Li(p,n)^{7}Be reaction features different configuration of neutron spectra (continuous and mono-energetic) with a relatively high neutron yield.

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