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A neutron-induced Single Event Effects facility at the 70 MeV Cyclotron of LNL-INFN

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Abstract

We describe a proposed neutron irradiation facility for studying neutron-induced Single Event Effects (SEE) in microelectronic components and systems at the new variable energy high current proton cyclotron (35-70 MeV; 750 µA) soon to be operational at LNL. We describe the progress in designing two neutron production targets to furnish continuous atmospheric-like neutron differential spectra: a W-based thick target (to stop 70 MeV protons), and an innovative composite target made of Beryllium and Tantalum or Lead. We also describe the layout of the facility that will also house quasi-monoenergetic neutron (QMN) and direct proton beam lines. The thick target beam line could be available as soon as the new cyclotron is commissioned. The composite target and QMN beam lines, to be designed in concert, would be completed soon after.

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Keywords: irradiation facility; neutron radiation effects; Single Event Effects; atmospheric neutrons.

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1. Introduction: neutron-induced Single Event Effects and neutron-effects studies at LNL

The effects of radiation on semiconductor microelectronic devices is an important field of scientific research and radiation tolerance is strategic for many applications of electronics. Technology trends in electronics towards smaller structures, lower operating voltages, higher clock speeds and growing system complexity bring an increased susceptibility of devices and systems to radiation effects induced by *atmospheric neutrons* produced in cosmic ray air-showers, cascades of particles initiated by very high energy galactic cosmic rays interacting with the atomic nuclei of the upper atmosphere. Atmospheric neutrons are of great concern for high altitude avionics, but are also of growing importance for ground-based commercial electronics, especially critical electronic systems such as computer servers, network routers, onboard computers, power devices and pacemakers.

A single neutron may disrupt the correct operation of a semiconductor microelectronic device if it causes the nucleus of a constituent atom of the device to recoil or break-up into one or more ionizing fragments. A Single Event Effect (SEE) is said to have occurred if a sensitive node collects enough secondary ionization charge to cause anomalous device behavior. Neutron-induced SEE types range from Soft Errors (SE) to catastrophic Hard Errors (HE): SE involve Single Event Upsets (SEU) that cause memory corruptions or changes in the logic functions; HE involve Single Event Latch-up (SEL) in CMOS technologies and Single Event Burn-out (SEB) in power MOSFETs.

Typically neutron-induced SEE occur when the energy of the impinging neutron is above some minimum threshold value E_{th}; the probability of a SEE to occur is usually expressed as an energy dependant cross-section $\sigma(E)$, a Weibull-like function that increases with neutron energy until a plateau value σ_P is reached. Atmospheric neutrons have a falling continuous differential energy spectrum $\varphi_0(E) = dN/dE$ ("white" energy spectrum) with a maximum energy well above 1 GeV. The sea-level rate R_0 of SEE in a device with N_{bits} multiple bits is given by:

$$R_0 = N_{bits} \times \int_{E_{th}}^{\infty} \sigma(E)\varphi_0(E)dE$$

Modern microelectronic devices and systems are now found to be sensitive to neutrons in the 1-10 MeV energy range, that comprises 40% of the atmospheric neutrons with $E > 1$ MeV. Instead HE such as SEL and SEB typically need higher energy neutrons ($E > 200$ MeV). At sea-level the integral flux of fast atmospheric neutrons ($E > 1$ MeV) is 21 neutrons/($\text{cm}^2 \times \text{hr}$) [JESD89A (2006)][Gordon et al. (2004)][Gordon et al. (2005)].

To study neutron induced effects in electronics, proton accelerators are used to produce high fluxes of neutrons by nuclear evaporation and spallation reactions. Thick neutron production targets made of heavy elements such as Tungsten (W) that completely stop the primary proton beam provide neutrons with white energy spectra. Moderators are added to shape the neutron energy spectrum to resemble the atmospheric one as much as possible in the accessible energy range. The maximum neutron energy E_{cut} from a white spectrum facility is clearly an important figure of merit. The most energetic white spectrum neutron source currently available is LANSCE at LANL in USA with a cut-off energy of 800 MeV. The future European Spallation Source (ESS) in Sweden will be able to furnish neutrons up to 2.5 GeV. Another important figure of merit is the acceleration factor F: the ratio of the neutron integral flux at the accelerator test facility to the natural flux, over an energy range of interest. If the accelerated energy spectrum $\varphi_{acc}(E)$ resembles the natural one up to E_{cut}, the accelerated rate R_{acc} of SEE in a device with multiple bits is given by:

$$R_{acc} = N_{bits} \times \int_{E_{th}}^{E_{cut}} \sigma(E)\varphi_{acc}(E)dE \approx F \times N_{bits} \times \int_{E_{th}}^{E_{cut}} \sigma(E)\varphi_0(E)dE$$

The acceleration factors of the existing and planned facilities range from 10^8 to a few 10^9 over their accessible energy ranges. An acceleration factor $F = 3\times10^9$ implies that one hour of irradiation is equivalent to more than 100 years of exposure at sea level. High acceleration factors ensure that useful numbers of SEE can be accumulated by experimenters in reasonable intervals of time. This is particularly important at facilities with low cut-off energies.

There is also a growing concern regarding SE susceptibility to low energy neutrons, mainly thermal neutrons. Boron (^{10}B), often present as a p-type dopant in semiconductors, such as in p-MOSFET, will promptly capture slow neutrons and break-up into alpha and lithium ionizing fragments. Atmospheric epithermal and thermal neutrons are copious; additional thermal neutrons are generated when the fast neutrons are slowed by moderating materials (concrete in buildings, or the fuel of aircraft) [Nakamura et al. (2008)].

The high ionizing capability of the neutron reaction products and the miniaturization of the electronics components increase the probability to induce a relevant damage in the operation of the electronic components.

2. The new neutron irradiation facility of Legnaro: the layout

A high-current (750 µA) variable energy (35-70 MeV) proton cyclotron is currently under construction for the INFN Legnaro labs (LNL) to be used as the primary driver for the Selective Production of Exotic Species (SPES) project [SPES (2008)][Prete et al. (2012)]. The basic accelerator complex will be commissioned in 2014. This accelerator will open up unique possibilities for neutron-effects studies in Italy.

A specialized neutron irradiation facility has been proposed to study neutron-induced SE effects in the neutron energy range accessible to the accelerator (more than 60% of fast atmospheric neutrons with E > 1 MeV are in the 1-50 MeV energy range), furnishing both white-spectrum and quasi-mono-energetic (QMN) neutrons [Bisello et al. (2011)]. The facility will not be able to study many important neutron induced effects that are known to occur at higher energies, such as SEL and SEB.

The neutron-induced SE (NISE) facility will provide four tools:

- two separate white-energy neutron beam lines with neutron differential energy spectra highly resembling the atmospheric one in the accessible energy range. The first beam line will use a thick W-based self-shielding production target that completely stops the proton beam. A spectrum shifter system (moderator) is then used to slow the neutrons and shape the energy spectrum to resemble the atmospheric one also down to epithermal and thermal energy ranges. The second line is based on a novel relatively thin composite production target made of Beryllium and a heavy element (such as Ta or Pb); with this approach the effective atmospheric-like neutron spectrum in the 1-60 MeV range is composed directly, without the use of moderators. In this case most of the proton beam passes through the target (losing 70% of the energy) without causing nuclear reactions. The spent beam is magnetically deflected towards a beam dump.
- a quasi mono-energetic neutron source (QMN) with a controllable peak energy. Initially the QMN neutrons will be obtained by using a few mm thick Beryllium (^{9}Be) production targets. Most of the proton beam (~ 90%) will pass through the targets and will be magnetically deflected towards a beam dump.
- a variable energy direct proton beam line for general purpose proton irradiations. Protons also induce SEE and can be used to study other radiation effects (displacement and total ionization dose damage effects).

Details of the white neutron production targets are given in Section 3. The QMN and proton lines are under preliminary design and are not described in detail in this contribution.

The floor plan of the NISE irradiation facility is shown in Figure 1. The thick W-based production target beam line in hall A8 is serviced by the B1 bending magnet (commissioned with the cyclotron) and will be the first to become available. The thinner composite target and the QMN beam lines coincide and share the same bending magnet and beam dump (hall A9). Although both white spectrum targets are designed to handle full power, neutron fluxes suitable for SEE studies can be achieved at the test points along the beam lines using only a fraction of the maximum proton current. As the thick W-based target is self-shielding, the first white spectrum line will be able to deliver very high neutron fluxes if necessary (to study very low probability SEE or for special applications). On the other hand, the maximum neutron fluxes on the composite target and QMN lines will be set by the design of the proton beam dump.

This neutron-induced SEE facility at LNL will be useful for research and studies of Soft Errors as microelectronics technology evolves to deeper sub-micron feature sizes. With regards to industrial applications, it must be said that the accelerator energy is too low for the LNL facility to be eligible as a validation facility for electronic Industries, both the discrete component/device providers and systems manufacturers. Industry, in this respect, is very conservative as clients require industrial products to pass standard tests. Testing standards do change, but very slowly. However the few test facilities that are recognized as standard are located at large accelerator laboratories, are expensive and difficult to access. For this reason a specialized, relatively inexpensive and accessible facility could be very useful for small electronics systems industries to check their innovative products for sensitivity to low energy neutrons.

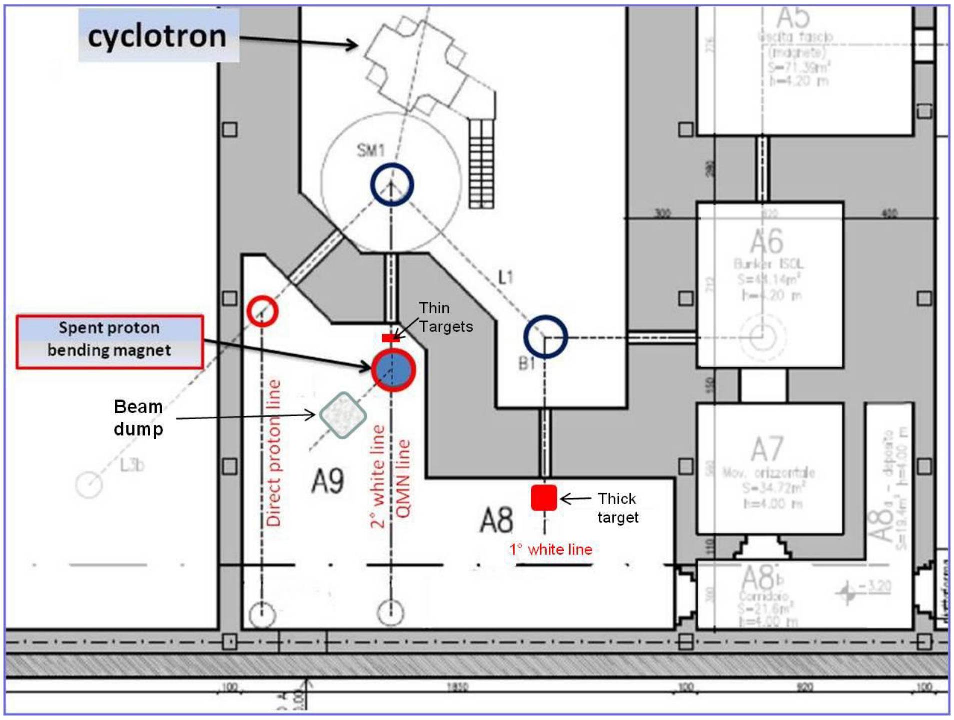

Fig. 1. A detail of the floor plan of the SPES facility showing the layout of neutron irradiation facility for SEE studies. The cyclotron is at the top. The switching SM1 and bending B1 magnets (blue) will be commissioned together with the cyclotron. The high flux white spectrum line, based on the thick W-based target in hall A8 (serviced by B1), will be available first. The QMN and second white spectrum target beam lines in hall A9 coincide and share the spent proton bending magnet and beam dump. The direct proton line is also in hall A9.

3. White-spectrum atmospheric-like neutron production targets

To produce white spectra, two high power production targets are under development. Both will deliver wide and uniform neutron beams to allow the irradiation of large electronic systems (e.g. entire computers, aircraft navigation systems…). The proton beam current will be adjusted to ensure useful SEE rates in devices under study. The production targets will be designed in order to sustain high power (up to 35 kW). The acceleration factor F at the proposed neutron-induced SEE facility can easily be made equal to those already available at existing facilities by using just a reduced fraction of the maximum available beam current from the SPES cyclotron.

The white neutron production target for the high flux beam line (the 1st white beam line in Figure 1) is a thick W-based self-shielding production target that completely stops the 70 MeV proton beam. The scheme is somewhat conventional: a water cooled target produces the largest possible amount of neutrons, moderators and reflectors are then used to shift the neutron energy and shape the energy spectrum to resemble the atmospheric one in the accessible energy range. A schematic of the water cooled W-target and a preliminary moderator system is shown in Figure 2.

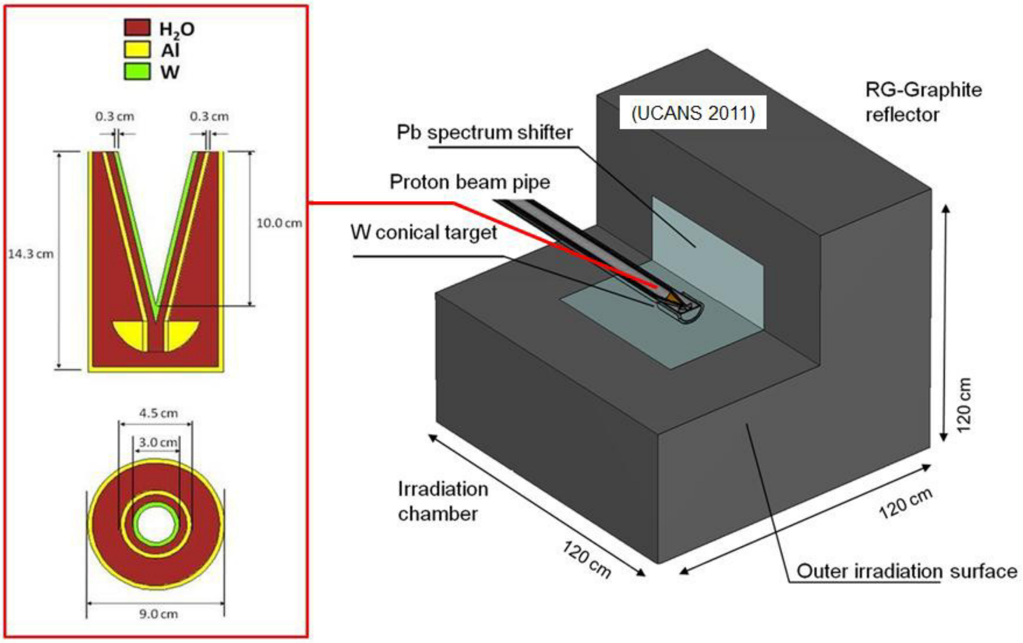

Fig. 2. The thick W water cooled neutron production target and a preliminary design of the spectrum shifting system.

A preliminary W-target system simulation was made using experimental angular and energy differential distributions of neutrons produced by 50 MeV protons on W [Aoki et al. (2004)]. The simulated neutrons were then transported through the water and aluminium (coolant and casing) and moderating materials (Pb and graphite), as in the preliminary system shown. The simulation of the W(p,xn)-stage was skipped because nuclear models implemented inside most codes are known to underestimate neutron yields by a factor 2-4 in the 50-80 MeV proton energy range. The surface-averaged differential energy spectrum on the whole front outer surface was calculated (the angular dependence of fast neutrons in the 1-45 MeV energy range is weak well out to 45^o) and two encouraging results were found: the shape of the differential neutron energy spectrum on the front surface was found to well agree with the sea-level atmospheric one down to epithermal energies; an acceleration factor of $F = 3\times10^9$ can be achieved using a proton beam current of 30 μA, about 5% of the maximum available [Bisello et al. 2012].

We are now performing 70 MeV proton simulations in steps. First the W(p,nx) stage was simulated with MCNPX (after a bench-mark simulation at 50 MeV was checked with data). Figure 3 shows the double differential distributions; the simulated data for different angles are multiplied by powers of 10 to aid inspection. Fast neutrons with E > 1 MeV were then transported through the water coolant and aluminum casing (the minimal target, without additional moderating materials) onto a circular area (radius 10 cm) placed 2 meters downstream centered at 0^o; the lethargy plot of the energy spectrum is also shown in Figure 3. The agreement with the atmospheric neutron spectrum is already quite good at higher energies (E > few MeV); the too few neutrons in the low energy bins is an artifact of transporting only fast neutrons. The next step will be to transport slow neutrons (E < 1 MeV). Moderators and reflectors will then be added to make a more complex target system. We will study separately the transport of fast and slow neutrons so as to optimize the final spectrum shape over a wide range of energies, down to thermal neutrons if possible. However, taking into account such a minimal system, without any spectrum shifter configuration, an acceleration factor of $F = 3 \times 10^9$ may be achieved with an estimated proton beam current of about 14 μA.

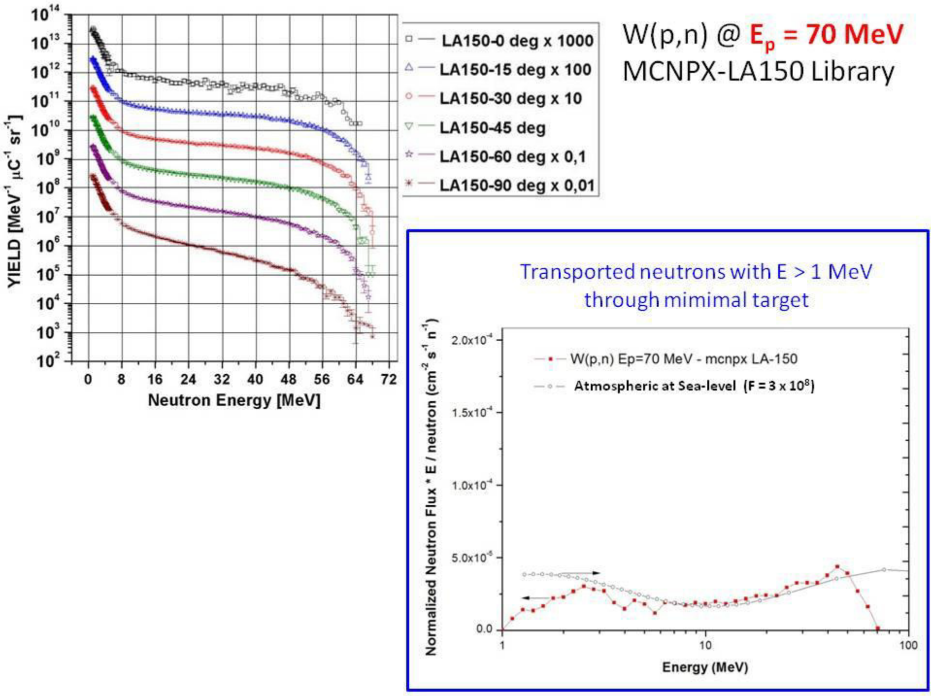

Fig. 3. The simulated (MCNPX) double differential neutron yields from W. In the blue rectangle, the lethargy energy spectrum of neutrons onto a circular surface 2 m downstream of the minimal target (the water cooled conically shaped W target shown in Fig. 2 without additional moderators).

A novel second white-spectrum production target is also under development. In this scheme, an effective atmospheric-like neutron spectrum is composed by a weighted convolution of neutrons coming from different target materials: a rotating composite target is made of arc-segments of different materials and different areas and the off-axis proton beam is intercepted by the different arc-segments (Figure 4). The choice of the material, area and thickness of the arc-segments is driven by the requirement that the composite target provides a suitably shaped differential energy spectrum and high neutron yield at test points.

To well reproduce the atmospheric neutron spectrum in the energy range up to almost 70 MeV, just two materials, Be and a heavy one, such as Pb or Ta, are enough [Bisello et al. (2012)]. The heavy material reproduces the lower MeV part of the spectrum and provides a long high energy tail; the light Be ensures that the high energy part of the spectrum remains nearly flat while providing good thermal-mechanical properties and high neutron yields.

Hydrogen build-up is a serious issue for target lifetime. This can be avoided by choosing a target thickness so that most of the beam passes through the target while losing ~ 70% of the energy. The spent beam is then bent by a dipole magnet and directed towards a dedicated beam dump. Thermal-structural studies have begun: Figure 4 shows a cross-section of the Be-Ta variant of the rotating composite target system and the temperature distribution resulting from a FEM simulation made for a 70 MeV proton beam current of 70 µA, 10% of full cyclotron power (1 cm beam spot). The off-axis proton beam (red arrow) alternatively strikes the Ta and Be arc-segments, respectively 5 mm and 26 mm thick. The inner surfaces of the arcs (radius 10 cm) are in thermal contact with circulating water (not shown) and kept at 40° C.

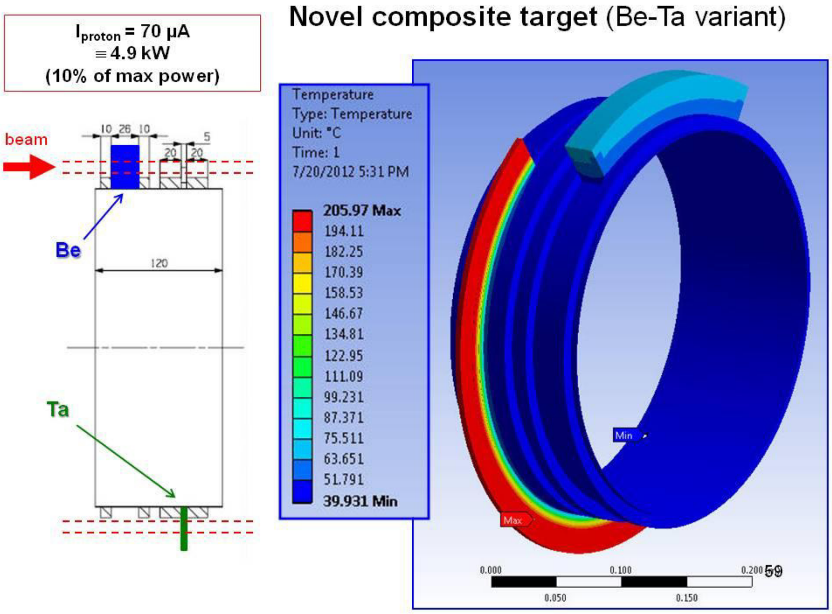

Fig. 4. Thermal FEM calculations of the rotating composite target (the Be-Ta variant). The off-axis proton beam (red arrow) alternatively strikes the Ta and Be arc-segments, respectively 5 mm and 26 mm thick. To increase power dissipation, the system is water cooled: the inner surface of the arc-segments are in thermal contact with a water cooled copper cylinder (not shown).

To obtain an acceleration factor of $F = 3\times10^9$, we estimate that a proton beam current of about 10 µA is sufficient; in practice the maximum usable proton beam current will be set by radio-protection constraints (activation of air) and the design of the beam dump. The present design overheats at full cyclotron power and further optimization might be considered.

The novel white-spectrum composite target system, without moderators, produces fast neutrons only and allows a flexible straightforward tailoring of the effective fast neutron energy spectrum. However it needs to be experimentally tested.

It is worth pointing out that the same concept can easily be adapted to produce QMN neutrons by using thin Be arcs.

4. Conclusions

The future neutron-induced SEE facility at LNL will be useful for research and studies of Soft Errors. It will represent a unique facility in Italy able to deliver a neutron beam with atmospheric-like energy spectra. We are confident that a specialized, relatively inexpensive and accessible facility, although non-standard, could prove to be very useful for small electronics industries to check their innovative products for unexpected sensitivity to lower energy neutrons, especially in the development and engineering phases, up to the final standard validation phase.

The present working group is in the process of obtaining funds from INFN to continue to develop and construct working high power neutron production target prototypes.

References

JESD89A "Measurement and Reporting of Alpha Particle and Terrestrial Cosmic Ray-Induced Soft Errors in Semiconductor Devices", Oct. 2006.

Gordon, M. S. , Goldhagen, P. , Rodbell, K.P., Zabel, T.H. , Tang, H.H.K., Clem, J.M., Bailey, P., "Measurement of the Flux and Energy Spectrum of Cosmic-Ray Induced Neutrons on the Ground", *IEEE Trans. Nucl. Sci.*, vol. 51, pp. 3427-3434, Dec. 2004.

Gordon, M. S., Goldhagen, P., Rodbell, K.P., Zabel, T.H., Tang, H.H.K., Clem, J.M., Bailey, P., Corrections to "Measurement of the Flux and Energy Spectrum of Cosmic-Ray Induced Neutrons on the Ground", *IEEE Trans. Nucl. Sci.*, vol.52, pp. 2703-2703, Dec. 2005.

Nakamura, T., Baba, M., Ibe, E. Yahigi, Y., *Terrestrial Neutron-Induced Soft Errors in Advanced Memory Devices*, World Scientific Publishing Co. Pte. Ltd, 2008.

SPES Technical Design Report 2008 ed. G. Prete and A. Covello INFN-LNL223 http://www.lnl.infn.it/spes/TDR2008/tech_design08_index.htm; http://www.bestcyclotron.com/product_70p.html

Prete, G., Andrighetto, A., Esposito, J., Mastinu, P., Wyss, J. The SPES project: a second generation ISOL facility, Physics Procedia, Volume 26, 2012, Pages 274-283

Bisello, D., Candelori, A., Dzysiuk, N., Esposito, J., Mastinu, P., Mattiazzo, S., Prete, G., Silvestrin, L., Wyss, J., A new irradiation facility for neutron-induced Single Event Effect studies at LNL, Radiation and Its Effects on Components and Systems (RADECS), Sep. 2011, Pages 760 – 766, DOI: 10.1109/RADECS.2011.6131462

Aoki, T. Baba, M., Yonai, S., Kawata, N., Hagiwara, M., Miura, T. , Nakamura, T., "Measurement of Differential Thick-Target Neutron Yields of C, Al, Ta, W(p,xn) for 50 MeV Protons", *Nuclear Science and Engineering*, vol. 146, pp. 200-208, 2004.

Bisello, D., Candelori, A., Dzysiuk, N., Esposito, J., Mastinu, P., Mattiazzo, S., Prete, G., Silvestrin, L., Wyss, J., Neutron production targets for a new Single Event Effects facility at the 70 MeV Cyclotron of LNL-INFN, Physics Procedia, Volume 26, 2012, Pages 284-293