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Experimental and numerical characterization of the neutron field produced in the n@BTF Frascati photo-neutron source

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ABSTRACT

A photo-neutron irradiation facility is going to be established at the Frascati National Laboratories of INFN on the base of the successful results of the n@BTF experiment. The photo-neutron source is obtained by an electron or positron pulsed beam, tuneable in energy, current and in time structure, impinging on an optimized tungsten target located in a polyethylene–lead shielding assembly. The resulting neutron field, through selectable collimated apertures at different angles, is released into a 100 m^2 irradiation room. The neutron beam, characterized by an evaporation spectrum peaked at about 1 MeV, can be used in nuclear physics, material science, calibration of neutron detectors, studies of neutron hardness, ageing and study of single event effect. The intensity of the neutron beam obtainable with 510 MeV electrons and its fluence energy distribution at a point of reference in the irradiation room were predicted by Monte Carlo simulations and experimentally determined with a Bonner Sphere Spectrometer (BSS). Due to the large photon contribution and the pulsed time structure of the beam, passive photon-insensitive thermal neutron detectors were used as sensitive elements of the BSS. For this purpose, a set of Dy activation foils was used. This paper presents the numerical simulations and the measurements, and compares their results in terms of both neutron spectrum and total neutron fluence.

1. Introduction

Fast neutron irradiation facilities are used in many fields, ranging from nuclear physics to radiation protection, material science, telecommunication, electronics, aerospace, defense and plant genetics. Besides neutron reactors and proton and ion accelerators, neutron beams are produced in electron facilities through photo-neutron processes on high-Z targets. Examples are Gelina (EC-JRC-IRMM Geel, Belgium) and nELBE (FZD Rossendorf, Germany) [1]. At The Frascati National Laboratories of INFN a photo-neutron irradiation source has been recently set up leading an electron or positron pulsed beam, tuneable in energy, current and in time structure, to impinge an optimized tungsten target located in a polyethylene–lead shielding assembly. The resulting neutron field, through selectable collimated apertures at different angles, is delivered to a 100 m^2 irradiation room. The neutron beam is characterized by an evaporation spectrum peaked at about 1 MeV. Using a 510 MeV electron beam, with time structure of 10 ns pulses at 1 Hz and charge per pulse $\approx$50 pC/pulse, the intensity of the neutron beam and its fluence energy distribution at a point of reference in the irradiation room were experimentally measured with a Bonner Sphere Spectrometer (BSS) and simulated with FLUKA and MCNPX Monte Carlo transport codes. The photon spectrum was also simulated.

Due to the large photon contribution and to the pulsed time structure of the beam, passive photon-insensitive thermal neutron detectors were used as sensitive elements of the BSS. For this purpose, a set of Dy activation foils was chosen.

A reference point located at 124 cm height from the floor and at 149 cm from the target center, perpendicularly with respect to the impinging electron beam (90° direction), was chosen for the experiment (see Figs. 1 and 2).

This paper presents the numerical simulations and the measurements, and compares their results in terms of both neutron spectrum and total neutron fluence.

2. The n@BTF field

The BTF (Beam Test Facility) [2,3] is part of the DAΦNE accelerator complex: it is composed of a transfer line, driven of a pulsed magnet that allows diversion of electrons or positrons, normally released to the DAΦNE damping ring, from the high intensity LINAC towards a 100 m^2 experimental hall. The facility

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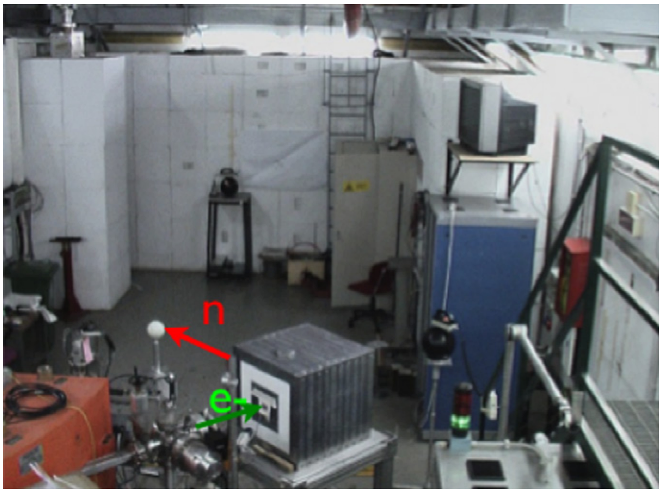

Fig. 1. n@BTF experimental layout.

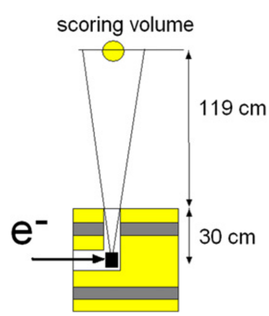

Fig. 2. Simplified scheme of the simulation geometry.

can provide electrons and positrons in a defined range of energy (up to 750 MeV for e^- and 510 MeV for e^+), charge ($<10^{10}$ e/pulse), pulse length (1–10 ns) and injection frequency (<50 Hz). The facility can operate at day and night times, with users coming mainly from Italy (about 50%) and all over Europe.

The n@BTF experiment was realized by dumping high-energy electrons on a properly optimized W target located in a previously studied [4] shielding structure in the BTF experimental hall, as shown in Fig. 1. The photons from the electromagnetic cascade may excite the W nuclei, resulting mainly in neutron production in the MeV region related to the Giant Resonance mechanisms. A few higher-energy neutrons (in the order of %) are expected from the Quasi-Deuteron and photo-pion mechanisms [2].

In order to accurately choose the material and the geometry of the target that maximizes the produced photo-neutrons many cylindrical configurations have been simulated by the Monte Carlo code, changing both the material and linear dimensions (length and radius) of the cylinder.

Several high-*Z* materials have been chosen as possible optimal candidates for the target: lead, tantalum and tungsten. Among all these materials tantalum and tungsten offer higher neutron yield, for the same target geometry, with respect to lead. Since the neutron yield for Tungsten is only slightly higher than for Tantalum, the final choice between these two materials has been done essentially on the base of thermo-physical properties: tungsten has a thermal diffusivity (which means more effective heat transfer by conduction) almost 3 times larger than that of tantalum.

In the performed simulations all the characteristics of the available electron beam (primary beam energy spread, spot size, energy distribution, etc.) have been taken properly into account. The optimization process has been carried out by estimating for each configuration the neutron fluence leaving the target and the neutron-to-photon fluence ratio in different directions with respect to the incident primary beam. We found that increasing the cylinder length of $5X_0$ (where X_0 is the radiation length of the electromagnetic cascade) from 10 to $15X_0$ would have lead to a corresponding enhancement in neutron yield of about 10%, while for going from $15X_0$ to 20 X_0, the gain would have been less than 3%. So a final cylinder length of $17X_0$ has been chosen (which identified the beginning of the plateau in the neutron yield curve). At the same time a fine-tuning of the final radius has been also performed so that, using the same optimization process, the optimum value for the radius has been determined to be $\simeq 10X_0$ (35 mm). As a result, a cylindrical target with radius 35 mm and length 60 mm was built.

Since the maximum electron beam spot size on the target is enclosed in a circle of 1 cm radius and the accuracy by which we can set the transversal beam size and its center is much better than a few mm, we can be confident that, even in the most disadvantageous case, all the energy of the primary electrons will be deposited in the target. Because the photo-neutron yield depends essentially on the value of the deposited energy, the estimated neutron yield sensitivity with respect to the examined geometrical parameters (beam spot size and radial location of the beam center) is actually negligible (less than 3%).

The lead–polyethylene–lead shield covers almost all the solid angle around the target, leaving only three free paths: the middle square window for the primary electron inlet, and two cylindrical holes for the neutron emission at directions 0° and 90° in a plane perpendicular to the electron beam impinging direction. Whilst the neutron field is practically isotropic, the photon fluence decreases by a factor of 10^2 from the 0° to the 90° direction.

3. Monte Carlo simulations

The FLUKA 2006.3 [5] and MCNPX 2.6 [6] codes were used to determine the neutron or photon fluence and their energy distributions. In FLUKA simulations, the photo-nuclear physics was activated over all the energy range for all the relevant heavy elements included in the model: natural W and Pb. In order to improve the statistics, a biasing technique was used, consisting in increasing the interaction probability of photons by a factor 100 (photon inelastic interaction length λ reduced by a factor 0.01). The neutron fluence per primary particle in the reference point and its energy distribution were estimated using both USRBDX and USRYIELD cards.

According to the FLUKA simulations, the neutron spectrum in the reference point is a Maxwellian-like distribution with peak energy at about 1 MeV and more than 99% of neutrons fluence below 20 MeV.

Concerning MCNPX, the calculations relied on the ENDF/B-VII [7] photo-nuclear data library. The $S(\alpha,\beta)$ data were used for the treatment of the thermal scattering in polyethylene. Both F4 and F5 tallies were used to determine the fluence energy distribution at the points of interest, obtaining coincident results within the simulation uncertainties ($<1\%$). Particularly, the F4 tally was based on a 10 cm diameter scoring sphere centered at the reference point. In the energy range of interest for this work, evaluated cross-section data are scarcely available and the codes rely on nuclear models describing the high-energy inelastic interaction in terms of intra-nuclear cascade (INC), pre-equilibrium and de-excitation models. For MCNPX, the Bertini high-energy interaction model was used.

The same geometry presented in Fig. 2 was adopted for both FLUKA and MCNPX simulations. The neutron and photon spectra are reported in Figs. 3, and 4, and 6, respectively.