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DEVELOPMENT OF SINGLE-EXPOSURE, MULTIDETECTOR NEUTRON SPECTROMETERS: THE NESCOFI@BTF PROJECT

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NESCOFI@BTF is a 3-y project (2011–13) supported by the Scientific Commission 5 of INFN (Italy). The target is the development of neutron spectrometers similar to the Bonner spheres, in terms of response energy interval and accuracy, but able to determine the neutron spectrum in only one exposure. These devices embed multiple (10 to 30) thermal neutron detectors (TNDs) within a single moderator. Two prototypes, called SPherical SPectrometer (SP^2) and cylindrical spectrometer (CYSP), have been set up. Whilst SP^2 has spherical geometry and nearly isotropic response, the CYSP has cylindrical geometry and is intended to be used as a directional spectrometer. Suitable active TNDs will be embedded in the final version of the devices. The resulting instruments could be used as real-time neutron spectrometers in neutron-producing facilities. This communication describes the design criteria, numerical analysis, experimental issues, state-of-the-art and future developments connected with the development of these instruments.

INTRODUCTION

Neutron fields with continuous spectra ranging in energy from thermal up to tens or hundreds of MeV are frequent in research, industry and medical fields. These fields may be intentionally produced, as in spallation neutron sources, or may be a parasitic effect, as in radiotherapy facilities or in aerospace applications. The point in common to all these applications is the need to characterise such neutron fields in terms of energy distribution of the neutron fluence (spectrum). The availability of an instrument able to monitor the neutron spectrum in real-time would significantly benefit most of these applications.

The Bonner sphere spectrometer (BSS) is still the only existing instrument that is able to respond over ten or more orders of magnitude in energy, although its energy resolution is known to be limited(1). In addition, it requires multiple exposures and time-consuming irradiation sessions and has no capability to operate as a real-time monitor (unless the field is so uniform that all spheres can be simultaneously exposed).

The NESCOFI@BTF project (2011–13) is operating in the direction of condensing the performance of the BSS in an active instrument based on several thermal neutron detectors (TNDs) embedded in a single moderator according to a well-defined geometry, thus resulting in a novel real-time monitor with spectrometric capabilities. The leading idea of the project is to develop two separate instruments, called SPherical SPectrometer (SP^2) and cylindrical spectrometer (CYSP), suited to cover the needs of different types of neutron-producing facilities. SP^2 consists of a spherical polyethylene moderator embedding thirty-one TNDs arranged in symmetrical positions along three axes. An internal 1-cm-thick lead shell, acting as (n,xn) radiator, allows responding to neutron of $E > 20$ MeV. This device measures the neutron spectrum disregarding its direction distribution. CYSP is a cylindrical moderator with seven TNDs located at different depths along the axis. An internal 1-cm-thick lead shell allows detecting high-energy neutrons. The CYSP response is sharply directional, and its collimating aperture defines the acceptance solid angle.

NESCOFI@BTF project involves eight researchers for an average manpower of ~2.7 FTE (full time equivalent) and a total budget of ~170 k€. The project activities have been distributed along the 3 y as follows:

Year 1 (2011): (1) theoretical design of SP^2 and CYSP using MCNPX 2.6(2), (2) fabrication of simplified prototype for the SP^2, operating with passive detectors (dysprosium activation foils) and calculation of the response matrix and (3) experimental verification of the response matrix with quasi-monoenergetic neutron fields (PTB Braunschweig).

Year 2 (2012): setting up suitable active TNDs plus a dedicated acquisition system. These fulfil the following target requirements: (1) miniaturisation—the target dimension for a single detector is in the order of 1 cm, (2) sensitivity and linearity—the spectrometers should work with dose rates ranging from μSv per h up to Sv per h, (3) excellent photon rejection and (4) low-cost—a single SP^2 includes thirty-one detectors, thus excluding for budget reasons practically all commercially available active TNDs.

The final decision was to develop customised detectors on the basis of low-cost commercial solid-state devices. Two types of active TNDs were produced, having different levels of cost and sensitivity:

The so-called 'thermal neutron pulse detector' (TNPD) produces a pulse-height distribution, from which the thermal neutron fluence can be derived. Typical thermal neutron sensitivity is 0.03 cm^2 (counts per unit fluence). The so-called 'thermal neutron rate detector' (TNRD) produces a voltage level that is proportional to the thermal neutron fluence rate. The lowest measurable thermal neutron flux is $\approx$100 cm^{-2} s^{-1}. The performances of these detectors are detailed in Pola *et al.*(3) and Bedogni *et al.*(4)

Year 3 (2013): fabricating and testing the final spectrometers equipped with active TNDs. The current state of these activities is as follows: (1) the active CYSP was fabricated and tested at the INFN-LNF with an Am-Be source. A more exhaustive testing campaign with quasi-monoenergetic neutron fields is planned in October 2013; (2) the active SP^2 is under fabrication.

THE SPHERICAL SPECTROMETER

Design and modelling

The design of the instrument is based on the results of simulations performed with MCNPX 2.6 Monte Carlo code(2), using the ENDF/B-VII cross section library(5) for neutrons with energies of <20 MeV and the room temperature cross section tables in polyethylene, S(α,β). Neutron transport of >20 MeV has been modelled using Bertini intra-nuclear cascade model and Dresner evaporation model(6).

The SP^2 spectrometer consists of thirty-one TNDs arranged along three perpendicular axes at five radial distances (5.5, 7.5, 9.5, 11 and 12.5 cm) and at the centre of a polyethylene sphere of diameter 25 cm. An internal 1-cm-thick lead shell between 3.5 and 4.5 works as an energy converter via (n,xn) reactions thus enhancing the response of >20 MeV, either for the central detector or for those located at 5.5 and 9.5 cm.

Although the response of a single TND in a given location is clearly not isotropic, a nearly isotropic response is obtained by averaging the readout of detectors located at the same radial response, as it has been discussed in previously published papers(7, 8). The same works also demonstrate the spectrometric capabilities of the device from thermal energies up to 100 MeV neutrons.

Experimental results

A passive SP^2 prototype was built on the basis of the final Monte Carlo model. Dysprosium activation foils(9–11) were exposed in selected cavities (see Figure 1), with the purpose of experimentally evaluating the simulated response matrix. As suitable testing fields, quasi-monoenergetic reference neutron fields of 0.147, 0.565, 1.2, 5.0 and 14.8 MeV available at PTB Braunschweig(12) were chosen.

The details of the experimental campaign are reported in Bedogni *et al.*(13) As a main result, the activation profile along the *X*-axis of the SP^2 (coinciding with the irradiation direction) was studied and compared with the 'expected' one, i.e. the activation profile obtained by folding the SP^2-simulated response matrix with the reference neutron spectra. According to the results, shown in Figure 2, it can be concluded that the simulated response matrix satisfactorily predicts the experimental spectrometer response for all investigated neutron energies. It should be noticed that the position corresponding to the

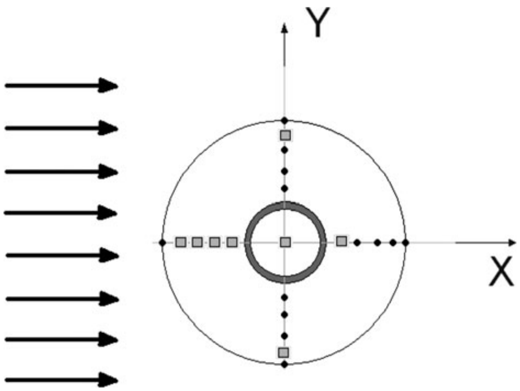

Figure 1. Sketch of the SP^2 irradiation geometry. A cut view of the sphere on the Z=0 plane is shown. The measurement positions used in the experiment are the grey squares (coordinates: $X=-11.0$, -9.5, -7.5, -5.5, 0.0, 5.5; $Y=-11.0$, 11.0).

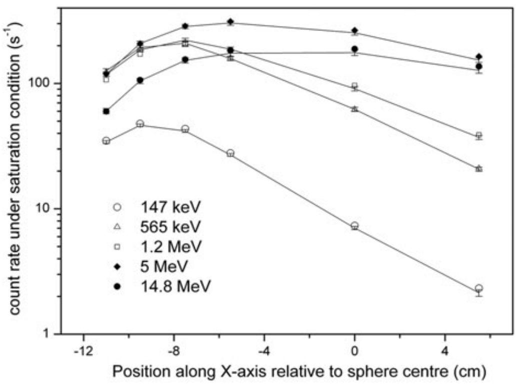

Figure 2. Saturation count rate measured in the dysprosium activation foils exposed in the selected positions of SP^2 for 0.147, 0.565, 1.2, 5.0 and 14.8 MeV (continuous lines). The expected count rates, obtained from the simulated response matrix, are also reported (symbols). Only the measurement positions along the *X*-axis of SP^2 were considered.

maximum of the profile shifts towards deeper positions as the energy increases. This effect constitutes the basis for using SP^2 as a neutron spectrometer.

THE CYLINDRICAL SPECTROMETER (CYSP)

Design and modelling

The CYSP spectrometer has been designed according to the conclusions of a detailed simulation study made with MCNPX 2.6., as it has been already described in 'The spherical spectrometer', concerning neutron cross section libraries and transport models.

The CYSP spectrometer mainly consists of a series of TNDs located along the axis of a polyethylene cylinder that provides spectral information when it is irradiated with a directional neutron beam.

The dimensions of the cylinder as well as the location of detectors have been optimised to achieve spectral resolution and practically eliminate the eventual contribution from epithermal neutrons coming from lateral directions. The collimator and the additional shielding made in borated plastic are included to eliminate such lateral contributions over the whole energy range.

As it is shown in Figure 3, the first part of the CYSP is a collimator 50 in diameter 30 cm in length made of polyethylene. The hole diameter is 8 cm, and is covered by 5-mm-thick borated plastic SWX-238. The main body of the spectrometer (right part in the figure) is a 35-cm-diameter polyethylene cylinder with seven detectors located along the axis. A lead disc has been inserted between 6th and 7th positions to increase the response to high-energy neutrons.

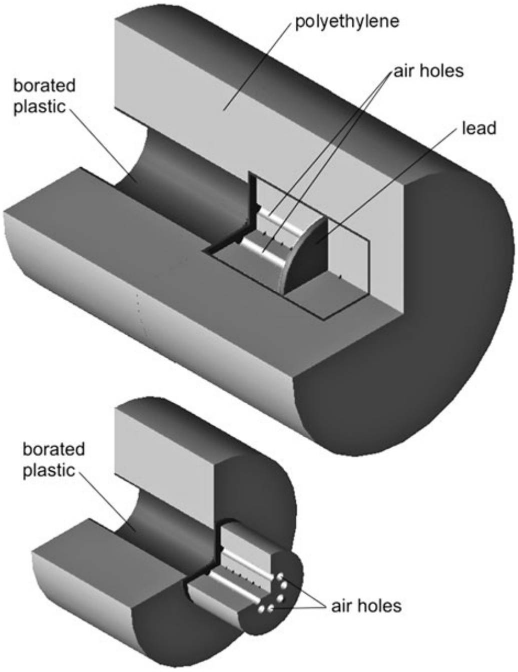

Figure 3. A 3D model of the CYSP spectrometer.

Experimental results

A prototype of the CYSP was fabricated, equipped with active detectors and tested in the neutron field from an Am-Be source (emission 2.09×10^6 s^{-1}) at the INFN-LNF. A high-scatter scenario, shown in Figure 4, was intentionally chosen with the aim of verifying the directionality of the CYSP response. This test included both simulations and experiments:

(1) The readings of the detectors placed at seven different depths along the CYSP axis were simulated in the absence and presence of the walls, ceiling and floor of the irradiation room. The difference is <1 % for positions 1 to 5, and 1–2 % for the deeper positions 6 and 7.

(2) The CYSP was irradiated as shown in Figure 4, and the detector readings were compared with those expected from the simulation. The experimental count rates varied from 0.09 s^{-1} (position 7) to 0.29 s^{-1} (position 2). The coherence between measured and simulated response is shown in Figure 5. The error bars combine the counting statistics and the response matrix overall uncertainty. The latter contribution provisionally was

Figure 4. Irradiation set up for testing the CYSP. A dummy source is located on the top of the tripod holder. The boron-lined mouth of the CYSP's neutron collimator is visible.

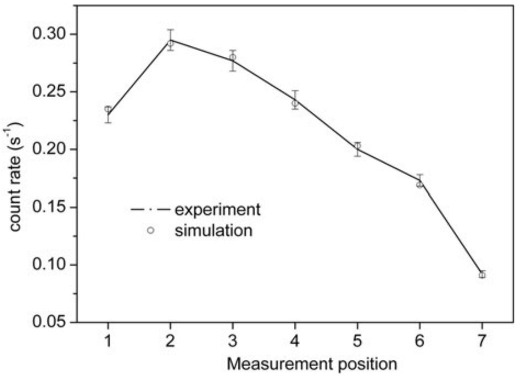

Figure 5. Profile of the count rate along the seven measurement positions of the CYSP. Uncertainty bars are ~3 %.

set to ±3 % on the basis of previous experience with the Bonner spheres and the SP^2(10, 13). However, this data will be accurately derived on the basis of an already planned calibration campaign with quasi-monoenergetic neutron fields.

The standard deviation of the ratio between measured and expected reading over the seven measuring positions is 2 %, thus demonstrating the accuracy of the simulation model.

CONCLUSIONS

Two prototypal single-moderator neutron spectrometers, called SP^2 and CYSP, were designed in the framework of the INFN project NESCOFI@BTF. They are intended to be used as isotropic or directional spectrometers, respectively. At present, the SP^2 response matrix was tested with passive detectors, whilst the active version of the instrument is under fabrication. In contrast, the active CYSP is available and its response matrix was partially tested with an Am-Be source, obtaining a very satisfactory agreement. A full test of the CYSP response matrix, using reference neutron fields, is planned before the end of 2013. After the active version of both SP^2 and CYSP will be set up and tested, these real-time on-line spectrometers could be replicated and distributed to third-party institutions under collaboration agreement.

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