Neutron spectrometry from thermal energies to GeV with single-moderator instruments*

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1 Introduction

Any practical neutron field spans in energy over ten or more decades, meaning from thermal energies up to the maximum production energy. Spectral measurements are almost invariably needed, because all neutron-induced effects (*e.g.* biological effects, errors in electronics equipment, response of materials) exhibit important energy dependence. 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 limited [1]. In addition, it requires multiple exposures and has no capability to operate as a real-time monitor.

The NESCOFI@BTF project (2011–2013) exploited the idea of an active instrument embedding several active thermal neutron detectors (ATND) in a single moderator according to a well-defined geometry, thus resulting in a novel real-time monitor with spectrometric capabilities. Two separate instruments were developed, called SP^2 and CYSP, suited to cover the needs of different types of neutron producing facilities. SP^2 (SPherical SPectrometer) consists of a spherical polyethylene moderator embedding thirty-one ATNDs arranged in symmetrical positions along the three axes. An internal 1 cm thick lead shell, acting as (n,xn) radiator, allows responding to neutron above 20 MeV. This device measures the neutron spectrum disregarding its direction distribution. The CYSP (CYlindrical SPectrometer) is a cylindrical moderator with seven ATNDs 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.

SP^2 and CYSP were theoretically designed [2,3] using MCNPX 2.6 [4]. A moderator prototype equipped with dysprosium activation foils [5] as passive detectors was then built to verify the feasibility of a practical instrument.

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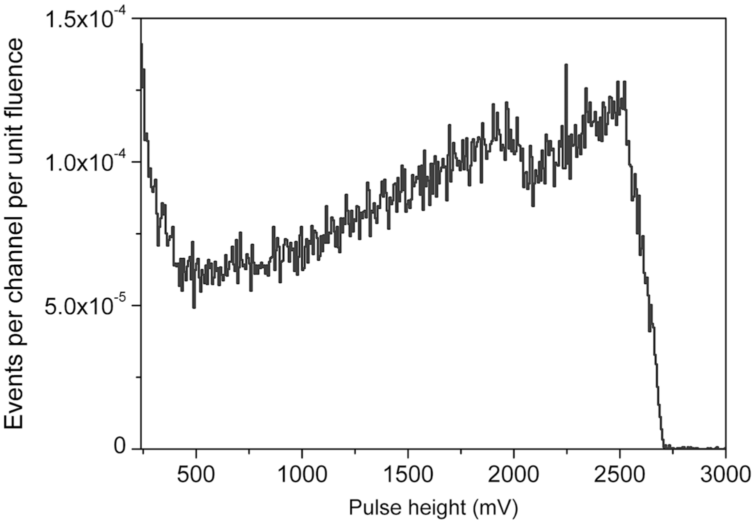

Fig. 1. Pulse height distribution from the TNPD with 30 μm of ^{6}LiF exposed to thermal neutrons. The double-peaked structure corresponds to the alpha and the triton. The tail in the initial portion of the spectrum corresponds to the secondary electrons.

This was experimentally tested with quasi-mono-energetic neutron fields [6]. The step from passive to active prototypes was made possible thanks to the development of dedicated ATNDs. Restrictive constraints were respected at this stage.

1) Miniaturization: the target dimension for a single detector was 1 cm.
2) Sensitivity and linearity: the spectrometers should work with dose rates ranging from μSv/h up to Sv/h.
3) Excellent photon rejection.
4) Low-cost: a single SP^2 includes up to thirty-one detectors, thus excluding for budget reasons practically all commercially available active thermal neutron sensors.

The final decision was to use commercially available, 1 cm^2 windowless sensitive area, type p-i-n silicon diodes, which response to thermal neutrons was enhanced by means of a ^{6}LiF layer. The deposition process was especially designed to process many detectors at the same time at basically no cost, apart that of the compound to be deposited.

Of the active sensors produced by the project [7,8], the so called "thermal neutron pulse detector", TNPD [7], was used to equip the active CYSP and SP^2. Prototypes of SP^2 and CYSP equipped with these active detectors were manufactured and tested in a variety of reference neutron fields.

2 Characterizing the prototypes

As anticipated in sect. 1, the "thermal neutron pulse detector" (TNPD), used to equip both SP^2 and CYSP prototypes, is a silicon diode covered with an appropriate thickness of ^{6}LiF. The neutron capture reaction in 6-lithium yields an alpha particle (2.05 MeV) and a triton (2.73 MeV), having range in LiF 6 μm and 30 μm, respectively. The optimal deposit thickness in terms of conversion efficiency corresponds to the range of the more penetrating reaction product, about 30 μm. The typical thermal neutron response of the TNPD with 30 μm of ^{6}LiF is 0.03 cm^2 (counts per unit thermal neutron fluence). The pulses from the detector are processed through a standard analog chain made of charge preamplifier and shaper amplifier, followed by a commercial digitizer (NI USB 6366) operating in streaming mode. The obtained pulse height distribution (see fig. 1) is analyzed to get the thermal neutron fluence. Particularly, "thermal neutron signal" (sum of alpha and triton peaks) is separated from the continuous distribution of secondary electrons (initial portion of the spectrum) with a simple threshold placed at about 600 mV.

The design of the instruments is based on the results of simulations performed with MCNPX 2.6 Monte Carlo code [2], using the ENDF/B-VII cross-section library [9] for neutrons with energies below 20 MeV and the room temperature cross-section tables in polyethylene, S(α, β). Neutron transport above 20 MeV has been modelled using Bertini intra-nuclear cascade model and Dresner evaporation model [10].

The CYSP mainly consists of a series of TNDs located along the axis of a polyethylene cylinder, see fig. 2.

The dimensions of the cylinder as well as the location of detectors have been optimized 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. The polyethylene collimator has external diameter 50 cm, internal diameter 16 cm, and length 30 cm. The internal cavity is lined with 5 mm of borated plastic SWX-238. After being selected in direction by

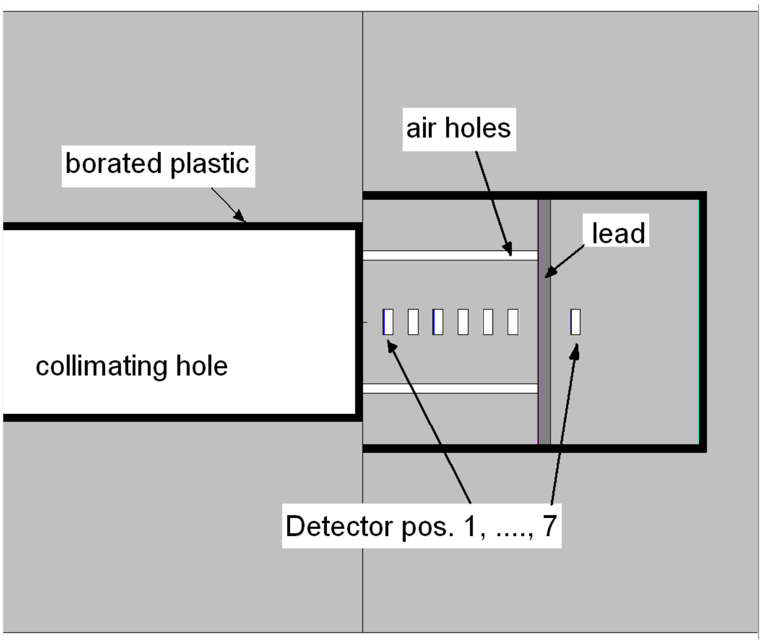

Fig. 2. Schematic cross-cut of the CYSP. Detectors cavities are visible along the moderator axis.

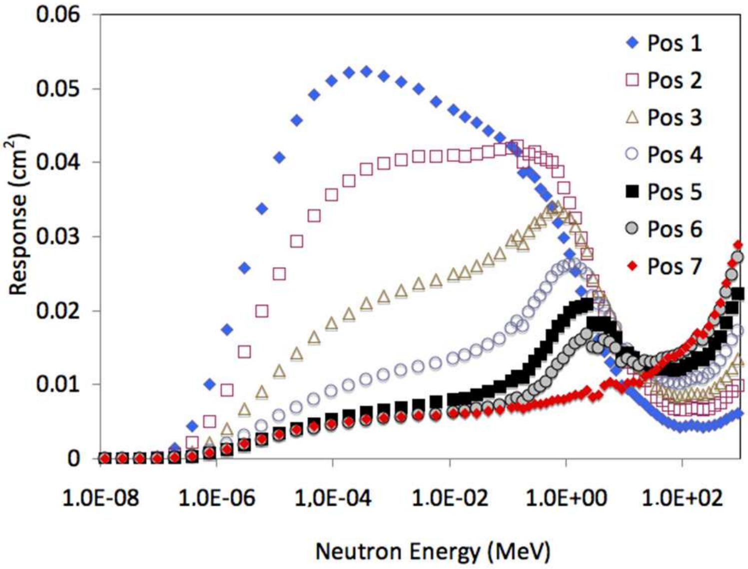

Fig. 3. CYSP response matrix.

the collimator, neutrons enter the detecting part of the instrument. This is a 35 cm diameter polyethylene cylinder allocating the seven TNPDs. A lead disk has been inserted between the 6th and 7th positions to increase the response to high-energy neutrons. The detecting part is contained in a borated plastic shell. Around the cylindrical axis, air holes enhance neutron streaming towards deep positions. Figure 3 shows the response matrix of CYSP derived with MCNPX. It expresses the expected number of counts in the TNPD, per unit neutron fluence, as a function of the neutron energy and the detector position. Pos 1 corresponds to the shallowest detector. Pos 7 corresponds to the detector under lead. The thermal component of the neutron field may be derived using an additional un-moderated TNPD placed at the collimator entrance. The accuracy of this Monte Carlo model was tested in reference quasi-mono-energetic neutron fields from 144 keV to 16.5 MeV at NPL (UK). This allowed estimating the response overall uncertainty in $\approx 2\%$ for the stated energy range.

The SP^2 spectrometer, as schematically shown in fig. 4, consists of thirty-one thermal neutron detectors arranged along three perpendicular axes at 5 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

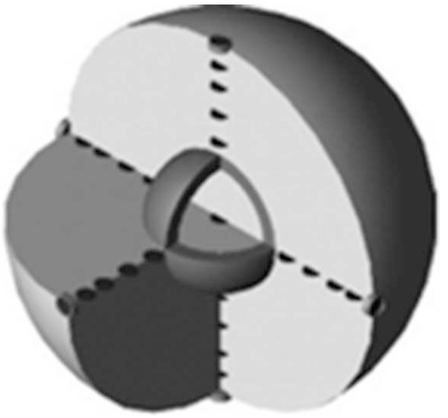

Fig. 4. Schematic view of the SP^2.

(n, xn) reactions thus enhancing the response above 20 MeV, either for the central detector and for those located at 5.5 and 9.5 cm. Although the response of a single TNPD in a given location is clearly not isotropic, earlier works showed that nearly isotropic response is obtained by averaging the reading of detectors located at the same radial response [2,3]. The response matrix of the device, intended as the average reading of detectors located at same radius, per unit fluence, as a function of the energy and of the radius, is similar to that of fig. 3. The response of SP^2 as a function of the irradiation geometry was verified using a reference neutron field of ^{241}Am-Be, ranging in energy from 0.1 to about 10 MeV, obtaining good agreement with the simulation model within $\approx 3\%$. In order to check in detail the energy dependence of the response, irradiations with quasi mono-energetic neutron fields are planned as in the case of the CSYP.

3 Conclusions

Two single-moderator neutron spectrometers, called CYSP and SP^2, were developed. Their energy response is similar to the Bonner spheres, but they allow determining the neutron spectrum in a single exposure. CYSP is a directional spectrometers and SP^2 is an isotropic spectrometer. CYSP response matrix was extensively tested in quasi-mono-energetic neutron fields from 144 keV to 16.5 MeV at NPL (UK), whilst SP^2 was tested in terms of directional response using an Am-Be neutron source. For both instruments the overall uncertainty of the simulation model was estimated as few % in the investigated energy range.

After completing the testing stage with high-energy neutron fields ($E > 20$ MeV), these real-time online spectrometers will be available for replication and distribution to third party institutions under collaboration agreement.

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References

1. D.J. Thomas, Radiat. Meas. **45**, 1178 (2010).
2. J.M. Gómez-Ros, R. Bedogni, M. Moraleda, A. Delgado, A. Romero, A. Esposito, Nucl. Instrum. Methods A **613**, 127 (2010).
3. J.M. Gómez-Ros, R. Bedogni, M. Moraleda, A. Esposito, A. Pola, M.V. Introini, G. Mazzitelli, L. Quintieri, B. Buonomo, Nucl. Instrum. Methods A **677**, 4 (2012).
4. D.B. Pelowitz (editor), MCNPX User's Manual Version 2.6. Report LA-CP-07-1473 (2008).
5. R. Bedogni, P. Ferrari, G. Gualdrini, A. Esposito, Radiat. Meas. **45**, 1021 (2010).
6. R. Bedogni, J.M. Gómez-Ros, A. Pola, M.V. Introini, D. Bortot, A. Gentile, A. Esposito, G. Mazzitelli, L. Quintieri, B. Buonomo, Nucl. Instrum. Methods A **714**, 110 (2013).
7. A. Pola, D. Bortot, M.V. Introini, R. Bedogni, A. Gentile, A. Esposito, J.M. Gómez-Ros, E. Passoth, A. Prokofiev, Radiat. Prot. Dosim. doi:10.1093/rpd/nct298.
8. R. Bedogni, A. Gentile, A. Esposito, A. Pola, M.V. Introini, D. Bortot, J.M. Gómez-Ros, Radiat. Prot. Dosim. **161**, 229 (2014).
9. M.B. Chadwick, P. Oblozinsky, M. Herman *et al.*, Nucl. Data Sheets **107**, 2931 (2006).
10. C. Pioch, V. Mares, W. Rühm, Radiat. Meas. **45**, 1263 (2010).