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CYSP-BEAM: A multi-detector directional spectrometer for in-beam neutron spectrometry

R. Bedogni [a,*], J.M. Gómez-Ros [a,b], K. Alikaniotis [a,c], G. Pagano [d], M. Pillon [d], A. Pietropaolo [d], M. Costa [e,f]

[a] INFN–LNF, via E. Fermi n. 40, 00044 Frascati (Roma), Italy
[b] CIEMAT, Av. Complutense 40, 28040 Madrid, Spain
[c] INFN Trieste, via Valerio 2, 34127 Trieste, Italy
[d] ENEA, Dept. Fusion and Technology for Nuclear Safety and Security, via E. Fermi 45, 00044 Frascati, Italy
[e] INFN Sezione di Torino, via Pietro Giuria 1, 10125 Torino, Italy
[f] Università degli Studi di Torino, Via P. Giuria 1, 10125 Torino, Italy

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ABSTRACT

CYSP-BEAM is a directional neutron spectrometer formed by a thick polyethylene cylindrical collimator followed by a sensitive capsule that contains several active thermal neutron detectors located at different depths along the cylindrical axis. Due to a thick lateral shield made of polyethylene and borated rubber, only neutrons from the direction identified by the collimating aperture can reach the internal detectors. As the response function of the internal detectors tend to peak at increasing energies as the detector depth increases, the device has spectrometric properties. This type of moderated spectrometer, whose prototype was the CYSP (CYlindrical SPectrometer), is capable to combine the functionalities of Bonner Spheres in a single device, thus requiring only one exposure to measure all the energy components of the incident beam, from thermal up to GeV neutrons. The neutron spectrum is obtained via few-channel unfolding methods. With respect to the original CYSP, the new CYSP-BEAM device is optimized to operate in the direct intense beam of neutron producing installations, such as large scale neutron science facilities. Compared with CYSP, CYSP-BEAM has narrower collimating aperture and the internal detectors have sensibility a factor 100 lower. Its response matrix was simulated using MCNPX. This paper describes the new device focusing on the internal detectors, the response matrix and the test measurement performed using the 14 MeV beam produced at the ENEA Frascati Neutron Generator (FNG).

1. Introduction

The idea of condensing the functionality of a Bonner Sphere Spectrometer in a single moderating device, embedding multiple thermal detectors in a specified geometry, was expressed in the past [1] but it needed about fifteen years to evolve in practical devices with real workplace applications. Two devices were developed during the present decade, namely the SP^2 (Spherical Spectrometer) [2–4] and the CYSP (CYlindrical SPectrometer) [5,6]. They were designed to cover the monitoring needs of different types of neutron-producing facilities. The neutron spectrum is obtained via few-channel unfolding methods [7].

SP^2 consists of a spherical polyethylene moderator embedding thirty-one thermal neutron sensors arranged in symmetrical positions along the three axes. This device has isotropic response and its main purpose is radiation protection.

By contrast, CYSP was designed to have sharply directional response. CYSP is a collimated HDPE (high-density polyethylene) cylinder with overall diameter 50 cm and total length 65 cm, including seven thermal neutron detectors located at different depths along the cylindrical axis. CYSP internal detectors are 1 cm^2 windowless p-i-n diodes made sensitive to thermal neutrons through evaporation-based deposition of a 30 μm layer of ^{6}LiF on the sensitive face [8,9]. CYSP spectrometric capabilities arise from the different response functions associated to the different detector positions. As the typical response of CYSP internal detectors is in the order of 0.01 cm^2 (counts per unit fluence incident on the spectrometer), the device was conveniently used in workplaces featuring fluence rate in the range (1 – 10^4) cm^{-2} s^{-1} [4,10].

A higher sensitivity version of CYSP, called CYSP-HS, was lately developed for measurements in very low-intensity fields, such as the neutron component of the cosmic field at ground level. This was achieved by increasing the sensitive area of the internal detectors by a factor of 15, approximately [11].

In view of the potential application of CYSP in the energy resolved characterization of neutron beamlines at large scale neutron science

* Corresponding author.
E-mail address: roberto.bedogni@lnf.infn.it (R. Bedogni).

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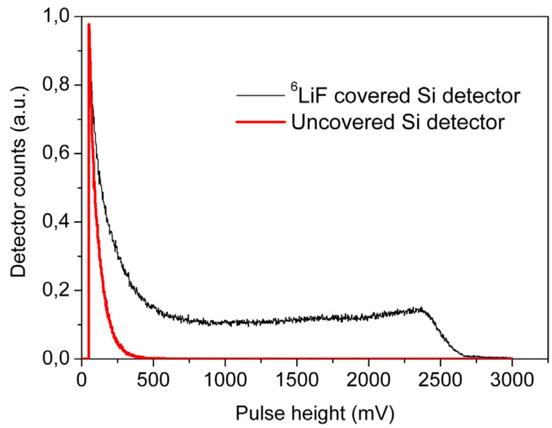

Fig. 1. Pulse height spectra registered by the uncovered (thick line) and ^{6}LiF covered detectors upon 14 MeV neutron irradiation with thermal neutrons from the HOTNES facility.

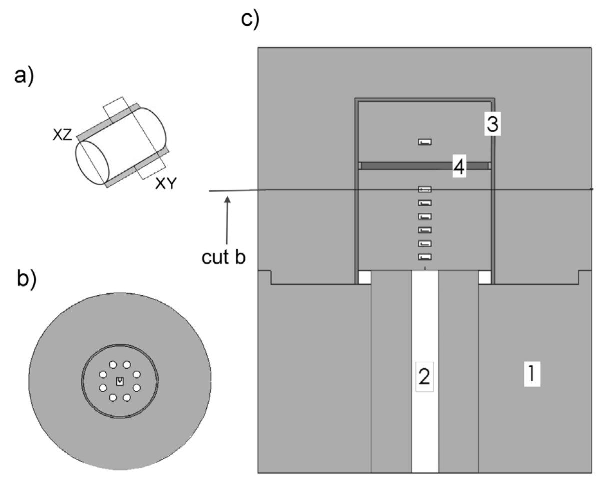

Fig. 2. Schematic view of the CYSP-BEAM: (a) indication of the planes used to draw the "b" and "c" cuts; (b) transversal cut view (XY plane) showing the air channels to enhance the response of deep detectors; (c) axial cut view (XZ plane) showing the HDPE collimator (1) 2.3 cm in diameter collimating hole (2), the borated rubber layers (3), the lead disk (4), and the detector positions. See the text for a complete explanation.

facility, a new version of the instrument was designed, namely CYSP-BEAM. It features small sensitive area (1 mm^2) thermal neutron detectors and a specifically designed collimator (length 30 cm, external diameter 50 cm, collimating aperture diameter 2.3 cm).

CYSP-BEAM response matrix was verified in the 14 MeV field of the ENEA Frascati Neutron Generator (FNG). This experiment allowed for the calibration the spectrometer and the evaluation of the accuracy of the simulated response matrix in the corresponding energy domain.

2. CYSP-BEAM internal detectors

Commercially available 1 mm^2 sensitive area silicon diodes deposited with 30 μm of 6LiF were used as thermal neutron sensors in the CYSP-BEAM. Before being assembled into the CYSP-BEAM, the detectors were individually tested using the HOTNES thermal neutron facility of ENEA-INFN Frascati [12–14]. Seven ^{6}LiF-covered detectors were tested, and their response to thermal neutrons was found to be (2.40± 0.01)×10^{-4} cm^2 (counts per unit fluence), the uncertainty accounting for detector-to-detector variability.

Fig. 1 Compares the typical pulse height spectrum from a bare diode and from a ^{6}LiF covered one.

The spectra were acquired using a spectrometry chain formed by a CREMAT CR110 charge preamplifier, a CREMAT CR200 shaper amplifier (shaping time 2 μs) and a commercial digitizer (NI USB 6366) operating in streaming mode. Whilst the "^{6}LiF covered" spectrum evidences the signals from the tritons and the alpha particles arising from the thermal neutron capture in the ^{6}LiF radiator, the "uncovered" spectrum mainly shows the gamma-induced secondary electrons. The detectors were used "unbiased" to maximize the difference between neutron and photon events. Referring to the ^{6}LiF-covered detector, neutron events can be easily separated from photon events by fixing a pulse height threshold at 600 mV. Pulses above this threshold are counted as neutron events. The "uncovered" spectrum does not show events above threshold, meaning that the gamma background does not affect the region of the "genuine" events. Thus, there is no need for "paired" measurements (covered and uncovered) to determine the neutron events in workplace measurements with CYSP-BEAM. A disadvantage of this method is that an important fraction (40%) of genuine neutron events are discarded as they fall below the threshold. However, this is acceptable in the high intensity applications of interest for this work.

3. The CYSP-BEAM spectrometer and its response

The concept of the CYSP was presented in previous publications [5, 6]. Compared to the CYSP, the CYSP-BEAM spectrometer includes the following significant modifications:

- As collimated neutron beams at large scale neutron science facilities have typical diameter in the order of few cm, CYSP-BEAM was equipped with a narrow collimating aperture (2.3 cm in diameter). By contrast, the CYSP collimator has 15 cm collimating aperture diameter.
- Because many beamlines used for neutron science (as in ISIS spallation source) have an important thermal neutron component, CYSP-BEAM collimating aperture is not lined with borated material, as that of CYSP is. Thus, differently than CYSP, CYSP-BEAM is sensitive to thermal neutrons.
- Internal thermal neutrons are silicon diodes with 1 mm^2 sensitive area covered with a 30 μm thick ^{6}LiF thermal neutron radiator. CYSP internal detectors have sensitive area 100 times larger.

The details of the CYSP-BEAM spectrometer are schematically shown in Fig. 2 CYSP-BEAM is a HDPE (high-density polyethylene) cylinder with overall diameter 50 cm and total length 65 cm. The dimensions of the cylinder and the location of detectors have been chosen to maximize the spectrometric capability of the device, i.e. the energy resolution corresponding to the response functions of the different detectors. The collimating aperture (labelled 2 in Fig. 2c) is 30 cm in length and 2.3 cm diameter. The seven thermal neutron detectors, located along the cylindrical axis, are contained in a HDPE capsule (20 cm in diameter, 30 cm in length) lined with borated rubber (thickness 5 mm), labelled 3. A lead disk, 1 cm thick, 20 cm in diameter (label 4), has been inserted between 6th and 7th positions to increase the response to high-energy neutrons. As it is shown in Fig. 2b, the detector capsule includes eight air holes, 1 cm in diameter, to enhance the response of deep detectors. The distance from their centres and the cylinder axis is 5 cm. The distance between two adjacent detector positions is 2 cm (centre to centre) for the first six detectors whilst the seventh is located behind the lead disk. Thus, the seven detectors are located at depths 2, 4, 6, 8, 10, 12 and 19 cm from the end of the collimator.

The response matrix (Figs. 3 and 4, same data with different scales) was calculated with the MCNPX 2.7 Monte Carlo code [15] using the modified track-length scoring option for the fluence (F4 tally). The "thermal neutron signal" in the detectors was assumed to be proportional to the number of (n, α) reactions within the ^{6}LiF converter layer. Thus the response matrix is the number of (n, α) reactions per unit incident fluence, as a function of the detector position and the neutron energy. The ENDF/B-VII cross section library [16] and the room temperature cross section tables in polyethylene, S(α, β), were

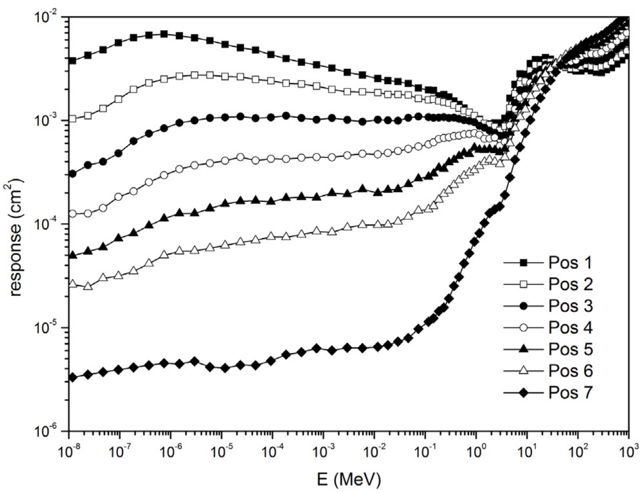

Fig. 3. The response matrix of CYSP-BEAM from thermal energies up to GeV.

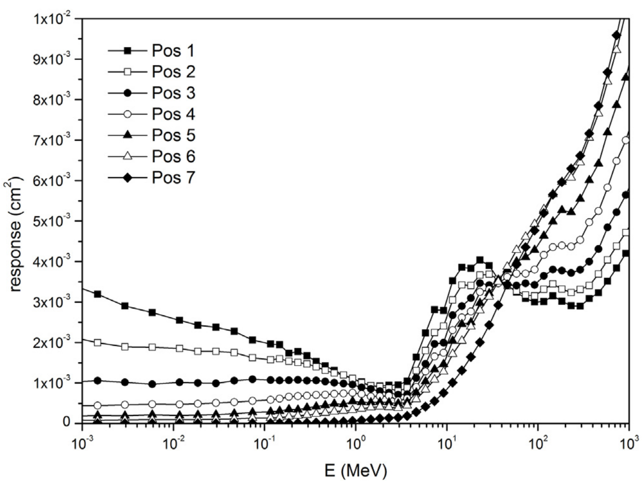

Fig. 4. The response matrix of CYSP-BEAM from keV up to GeV.

used for neutrons with energies below 20 MeV whilst the Bertini intra nuclear cascade model and the Dresner evaporation model were used for neutrons with energies above 20 MeV [17]. A cut-off in the number of histories has been applied to obtain statistical uncertainties lower than 3% in all cases.

The simulated response matrix, represented in Figs. 3 and 4, is $M_i(E)$, where pedix "i" denotes the detector position. The real response matrix, $C_i(E)$, is the number of measured counts, per unit incident fluence, as a function of the energy and the detector position. Because not all the neutron capture events in the ^{6}LiF radiator produce measurable signals in the diode, the ratio between $C_i(E)$ and $M_i(E)$ is lower than 1 and represents the *spectrometer calibration factor*, F. If the simulated response well describes the actual spectrometer response, F should not depend on the measurement position and the neutron energy. The variability of F, with the measurement position and the energy, can be used to estimate the overall accuracy of the simulated response matrix in the energy range considered [18].

4. Calibration of CYSP-BEAM in the 14 MeV FNG field

The irradiation took place at FNG, the accelerator-driven 14 MeV neutron source operating at the ENEA Frascati Research Centre [19]. The neutron emission rate is measured by means of the so-called associated alpha particle technique [20] using a calibrated Silicon Detector placed inside the drift tube and subtending a small and well-known solid angle to the FNG's target. The experimental hall housing the source is $12 \times 12 \times 9$ m^3, the neutron-producing target is approximately located at the centre of the experimental hall. The front face of the CYSP-BEAM was located at 60 cm from the target in the forward direction (Fig. 5), where the expected monochromatic neutron energy was 14.7 MeV. To estimate the room-scatter contribution to the CYSP-BEAM readings, the shadow-cone irradiation technique was used [21]. The shadow cone had length 50 cm, maximum diameter 25 cm, minimum diameter 8 cm, and was made of high-density polyethylene plus a 0.5 cm thick borated rubber on the large end. Its small end was placed at 4 cm from the neutron emitting target. The effectiveness of this cone design was previously verified by means of MCNP simulations. The irradiations were performed at a neutron emission rate at the target of 4.4×10^{10} s^{-1}, with typical exposure time 900 s.

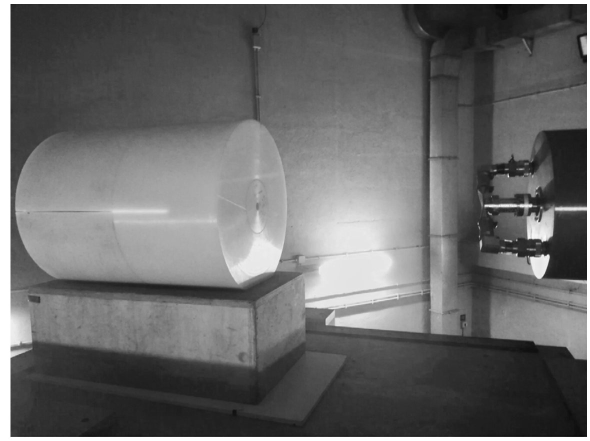

Fig. 5. Experimental set-up. The CYSP-BEAM front face was located at 60 cm from the target in the forward direction, using a low-scatter holder.

The CYSP-BEAM readings were corrected for the scattered radiation by subtracting the "shadow-cone" readings from the corresponding "total field" readings. The contribution of the scattered radiation to the instrument reading (ratio between "shadow bar" and "total field" reading) ranged between 6% (Position 1) to 16% (Position 7).

Seven estimations (one per detector position) of the CSYP-BEAM calibration factor were carried out as follows:

$$F_i = \frac{\frac{C_{i,tot}}{n_{tot}} - \frac{C_{i,cone}}{n_{cone}}}{M_i} \quad i = 1\ldots,7 \tag{1}$$

Where the symbols represent:

– $C_{i,tot}$ the CYSP-BEAM counts in the ith detector position in the total field irradiation;

– $C_{i,cone}$ the CYSP-BEAM counts in the ith detector position in the irradiation with the shadow-cone;

– n_{tot} the number of target-emitted neutrons in the total field irradiation;

– n_{cone} the number of target-emitted neutrons in the irradiation with the shadow-cone;

– M_i the expected number of neutron capture reactions in the ^{6}LiF converter of the ith detector position, per target-emitted neutron, in an ideal scatter-free irradiation condition. This number was obtained with MCNPX, using the realistic FNG neutron emission spectrum [19].

The F_i values experimentally obtained are reported in Fig. 6. The contributions to the uncertainties, lower than 7%, come from FNG emission rate and spectrum, detector positioning and alignment, electronics and counting.

The best estimation of the calibration factor, F, was then obtained by a weighted average of the F_i values. Its numerical value is F =(1.79± 0.04)×10^{-2}. This ± 2.3% figure can be regarded as an estimation of

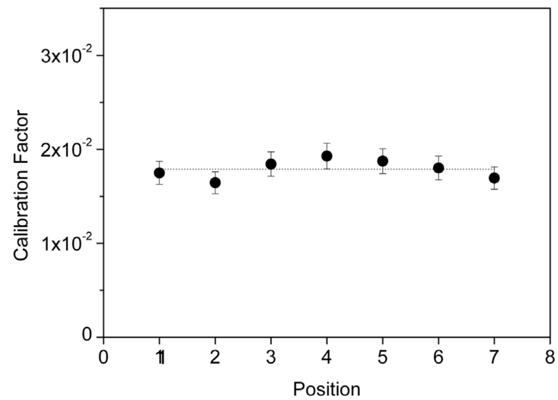

Fig. 6. Estimation of the CYSP-BEAM calibration factor for different detector positions.

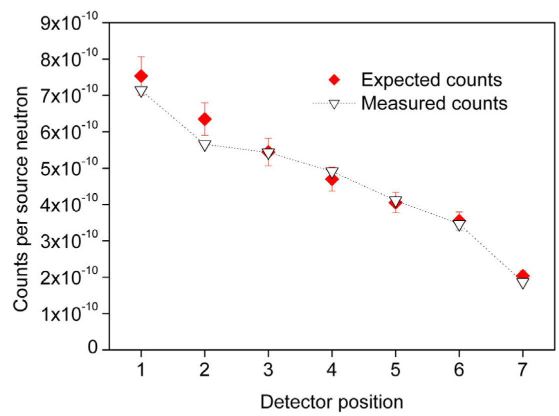

Fig. 7. Simulated and measured CYSP-BEAM counts per emitted neutron.

the "overall uncertainty" of the simulated response matrix for the investigated energy range.

If the M_i values are multiplied by F, the Monte Carlo simulation is properly scaled and can be directly compared with the experiment. This is done in Fig. 7, where the observed counts per emitted neutrons are compared with $F \times M_i$ (expected counts).

5. Conclusions

A directional, single-moderator, multi-detector neutron spectrometer called CYSP-BEAM was designed to operate in intense neutron beams. Its design is similar to that of the well-known CYSP spectrometer, but a narrower collimator (2.3 cm in diameter) and smaller internal detectors (1 mm^2 ^{6}LiF-covered Silicon diodes) are used. Its energy response extends from thermal to GeV neutrons, and the typical response of its internal detectors at 10 MeV is in the order 10^{-5} cm^2. The CYSP-BEAM response matrix, derived by means of MCNPX calculations, was experimentally verified in the well-established 14 MeV field of the Frascati Neutron Generator. This allowed for the determination of the spectrometer calibration factor and the overall uncertainty of the response matrix at 14 MeV, resulted in ±2.3%. This uncertainty figure is comparable with that of well-established moderator-based spectrometers, as Bonner spheres [18]. The device described in this work can find application in the routine quality control of neutron beams at large scale neutron science facilities, as the ISIS spallation source or the future European Spallation Source.

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References

[1] V. Vylet, A. Fassò, N. Luckau, A new/old type of neutron spectrometer, in: Proceedings of the IRPA Regional Symposium on Radiation Protection in Neighbouring Countries of Central Europe, Czech Republic, 1998, 8–12 Sep 1997, p. 671.
[2] R. Bedogni, D. Bortot, A. Pola, M.V. Introini, M. Lorenzoli, J.M. Gomez-Ros, D. Sacco, A. Esposito, A. Gentile, B. Buonomo, M. Palomba, A. Grossi, Nucl. Instrum. Methods A 780 (2015) 51.
[3] R. Bedogni, D. Bortot, B. Buonomo, A. Esposito, J.M. Gómez-Ros, M.V. Introini, G. Mazzitelli, M. Moraleda, A. Pola, A.M. Romero, Radiat. Prot. Dosim. 170 (1–4) (2016) 326.
[4] J.M. Gómez-Ros, R. Bedogni, D. Bortot, C. Domingo, A. Esposito, M.V. Introini, M. Lorenzoli, G. Mazzitelli, M. Moraleda, A. Pola, D. Sacco, Radiat. Prot. Dosim. 173 (1–3) (2017) 104.
[5] J.M. Gómez-Ros, R. Bedogni, D. Bortot, B. Buonomo, A. Esposito, A. Gentile, M. Lorenzoli, M.V. Introini, G. Mazzitelli, M. Moraleda, A. Pola, D. Sacco, Radiat. Meas. 82 (2015) 47.
[6] R. Bedogni, J.M. Gómez-Ros, A. Pola, D. Bortot, A. Gentile, M.V. Introini, B. Buonomo, M. Lorenzoli, M. Mazzitelli, D. Sacco, Nucl. Instrum. Methods A 782 (2015) 35.
[7] M. Matzke, Radiat. Prot. Dosim. 107 (1–3) (2003) 155.
[8] A. Pola, D. Bortot, M.V. Introini, R. Bedogni, A. Gentile, A. Esposito, J.M. Gómez-Ros, E. Passoth, A. Prokofiev, Radiat. Prot. Dosim. 161 (2014) 229.
[9] R. Bedogni, D. Bortot, A. Pola, M.V. Introini, M. Lorenzoli, J.M. Gómez-Ros, D. Sacco, A. Gentile, B. Buonomo, M. Palomba, A. Grossi, Nucl. Instrum. Methods A 780 (2015) 51.
[10] R. Bedogni, M. Costa, J.M. Gómez-Ros, V. Monti, A. Pola, A. Kreisel, S. Halfon, D. Kijel, L. Weissman, Nucl. Instrum. Methods A 902 (2018) 144.
[11] R. Bedogni, J.M. Gómez-Ros, A. Pola, M. Treccani, M. Costa, Appl. Radiat. Isot. 142 (2018) 38.
[12] R. Bedogni, A. Sperduti, A. Pietropaolo, M. Pillon, A. Pola, J.M. Gómez-Ros, Nucl. Instrum. Methods A 843 (2017) 18.
[13] R. Bedogni, A. Pietropaolo, J.M. Gomez-Ros, Appl. Radiat. Isot. 127 (2017) 68.
[14] A. Sperduti, M. Angelone, R. Bedogni, G. Claps, E. Diociaiuti, C. Domingo, R. Donghia, S. Giovannella, J.M. Gomez-Ros, L. Irazola-Rosales, S. Loreti, V. Monti, S. Miscetti, F. Murtas, G. Pagano, M. Pillon, R. Pilotti, A. Pola, M. Romero-Expósito, F. Sánchez-Doblado, O. Sans-Planell, A. Scherillo, E. Soldani, M. Treccani, A. Pietropaolo, J. Instrum. 12 (2017) P12029.
[15] D.B. Pelowitz, MCNPX user's manual version 2.7, 2011, Report LA-CP-11-00438.
[16] M.B. Chadwick, P. Oblozinsky, H. Herman, et al., Nucl. Data Sheets 107 (2006) 2931.
[17] C. Pioch, V. Mares, W. Rühm, Radiat. Meas. 45 (2010) 1263.
[18] R. Bedogni, A. Pola, V. Monti, M. Costa, D.J. Thomas, Nucl. Instrum. Methods Phys. Res. A 897 (2018) 18.
[19] A. Pietropaolo, F. Andreoli, M. Angelone, U. Besi Vetrella, S. Fiore, S. Loreti, G. Pagano, R. Pilotti, M. Pillon, J. Phys. 1021 (2018) 012004.
[20] T.R. Fewell, Nucl. Instrum. Methods 61 (1968) 61.
[21] ISO, International Standardization Organization, Reference Neutron Radiations - Part 2: Calibration Fundamentals of Radiation Protection Devices Related to the Basic Quantities Characterizing the Radiation Field, ISO, 2000.8529-2:2000.