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Testing a newly developed single-sphere neutron spectrometer in reference monochromatic fields from 147 keV to 14.8 MeV

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ABSTRACT

A new neutron spectrometer, designed to simultaneously respond from the thermal domain up to hundreds of MeV neutrons, was designed and built in the framework of the INFN project NESCOFI@BTF. It has been called SP^2 (SPherical SPectrometer) and it consists of 31 thermal neutron detectors embedded in a 25 cm diameter polyethylene sphere with an internal 1 cm thick lead shell. The new spectrometer shows similar performance as the Bonner sphere spectrometer, but has the notable advantage of requiring only one exposure to determine the whole spectrum. The SP^2 response matrix, previously calculated with MCNP, has been experimentally evaluated with monochromatic reference neutron fields from 147 keV to 14.8 MeV at PTB Braunschweig. As suitable thermal neutron detectors, Dysprosium activation foils were adopted at this stage. The results of the experiment confirmed the correctness of the response matrix within an overall uncertainty of ±3%. The next phase of the NESCOFI@BTF project will be the replacement of passive detectors with active counters, thus leading to a real-time spectrometric monitor that is expected to significantly innovate the neutron control task in neutron-producing facilities, such as the beam-lines for industrial irradiation or condensed matter studies.

1. Introduction

The Bonner sphere spectrometer is still the only existing instrument that is able to respond from thermal energies up to hundreds of MeV neutrons, even if the energy resolution is known to be limited [1]. In addition, it has a notable disadvantage that is the need to sequentially irradiate the spheres. This produces two main consequences:

– the irradiation sessions are time-consuming, because a BSS is typically composed of more than ten spheres; and
– the BSS could never be adopted as a real-time spectrometer.

The performance of the BSS in terms of energy interval would be highly desirable in most measurement applications of industry, research and medical field. However, its use on large scale is prevented by the inability to provide a real-time monitoring.

The NESCOFI@BTF project is operating in the direction of condensing the performance of the BSS in a single moderator, thus opening the way to a novel real-time monitor with spectrometric capabilities. This device is called SPherical SPectrometer (SP^2) and consists of a spherical moderator embedding 31 thermal neutron detectors 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. A final design, optimizing the external diameter, the number and position of the thermal neutron detectors, the position and thickness of the lead shell, was achieved through Monte Carlo calculations and published in a previous paper [2]. The same work also demonstrates, relying on the simulated response matrix, that this device has spectrometric capabilities from thermal energies up to hundred MeV neutrons. The response matrix of this configuration, intended as the reading of each thermal neutron detector per unit fluence as a function of the energy and of the irradiation geometry, is also known by simulation.

A prototype was built on the basis of this model. Air cavities with 12 mm diameter and 0.1 mm thickness were left in place of the thermal neutron detectors. Dysprosium activation foils were positioned in the cavities, with the purpose of experimentally evaluating the simulated response matrix. As suitable testing fields, monochromatic reference neutron fields of 0.147, 0.565,

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1.2, 5.0 and 14.8 MeV available at PTB Braunschweig were chosen. From this experiment the following results are expected:

- Verifying that the simulation model of the SP^2 is correct. This was done by comparing the observed foil activity with that calculated by folding the SP^2 response matrix with the reference monochromatic neutron spectra.
- Estimating the overall uncertainty of the simulated response matrix.

It should be recalled that the selected reference fields only cover the low neutron energy domain ($E < 20$ MeV), whilst the instrument can respond up to hundreds of MeV. The remainder portion of the energy interval will be covered by a further experiment, for which a well-established low-energy response matrix is a crucial pre-requisite. This is because high-energy reference fields are always accompanied by a low-energy component (some tens per cent in fluence), for which accurate correction is needed.

Moreover, because the chosen monochromatic fields are in practice monodirectional, the SP^2 response matrix was only tested for this particular irradiation geometry.

The validation experiment described in this work allowed launching the next phase of the NESCOFI@BTF project, i.e. the replacement of activation foils with active thermal neutron detectors. This will result in the desired real-time spectrometric monitor that is the main target of the project. This active instrument is expected to significantly innovate the neutron control in accelerator-based neutron beam-lines, such as those for industrial irradiation or condensed matter studies. To date, various detectors have been proposed for neutron monitoring in these facilities, namely diamonds [3], GEM [4], TFBC [5] or even extended range Bonner sphere spectrometers (ERBSS) [6,7]. Diamonds, GEM and TFBC are good real-time monitors but only see a restricted energy interval and are not suited to control variations in the neutron spectrum. On the other hand the ERBSS accurately measures the neutron spectrum but cannot operate as real-time monitor. The active SP^2 will finally unify these characteristics, providing unique measurement features:

(1) Continuously monitoring the beam in terms of energy-integrated fluence rate and its energy distribution.
(2) Detecting deviations from nominal beam characteristics, possibly ascribable to the target, the primary beam, the irradiated samples or the materials present in the irradiation room.

2. SP^2 response

According to the final design described in previous work [2], the SP^2 is a polyethylene sphere with external diameter 25 cm. This embeds an internal 1 cm thick lead shell with internal diameter 7 cm. One measurement position (i.e. a cavity for positioning a thermal neutron detector) is located at the centre of the sphere, and 30 additional foils have been symmetrically arranged along three perpendicular axes at five radial distances: 5.5, 7.5, 9.5, 11 and 12.5 cm (see Fig. 1). The six detectors at 12.5 cm are located on the surface of the sphere. These are separated from the sphere by a 1 mm cadmium (Cd) layer, and are only intended to estimate the thermal neutron component of the field. The Cd foil eliminates the contribution of neutrons backscattered from the sphere.

The use of natural Dy as activation material in moderated spectrometers is well established [6,8,9] and relies on the high neutron activation cross-section of ^{164}Dy and on the short half-life of the ^{165}Dy (2.334 h). After irradiation the foils are counted in a portable beta-counter.

The response matrix of the SP^2, $M_i^{geom}(E)$ (units cm^2), is presented in Ref. [1]. It represents the number of (n, γ) capture events in ^{164}Dy per unit incident neutron fluence as a function of the measurement point, of the neutron energy and of the irradiation geometry. Pedix "*i*", with $i = 1,..,31$, denotes the measurement position within the sphere; apix "*geom*" denotes the irradiation geometry under which the response matrix was derived. Previous studies [10,11] showed that the quantity obtained by averaging the reading of the six detectors located at the same radius within the sphere (called "six-points-average") is basically geometry-independent, thus demonstrating that the device has isotropic response. However, as previously stated, the only irradiation geometry of interest for this work is the monodirectional one, symbolized with (100). This symbol means that a broad monodirectional neutron beam impinges the sphere along the *X*-axis. This is shown in Fig. 2.

If $\dot{\Phi}(E)$ (units cm^{-2} s^{-1} MeV^{-1}) is the energy-dependent neutron fluence rate (reference data provided by PTB), the integral $f_i^{100} = \int dE\, M_i^{100}(E)\, \dot{\Phi}(E)$ is expected to be proportional to the count rate measured in the foils under saturation irradiation condition (called C_i, where "*i*" denotes the position). The procedure needed to obtain C_i from the result of the beta counting needs corrections for (1) the decay between the end of the irradiation and the beginning of the measurement, (2) the decay during the measurement and (3) the fraction of the saturation activity reached during the irradiation [12].

The ratio between C_i and f_i^{100}, is called the *spectrometer calibration factor*, *F*.

If the simulated response well approximates the real spectrometer response, *F* does not depend from the measurement position. This is actually the philosophy followed in this work to evaluate the simulated response matrix. For every monochromatic energy and eight selected measurement positions within the SP^2, the calibration factor $F_{i,E}$ (where *i* denotes the measurement position and *E* denotes the monochromatic energy) was experimentally derived. The information on the accuracy of the simulated response matrix was obtained from the distribution of the $F_{i,E}$ values. These selected positions are shown as grey squares in Fig. 2 and correspond to the following coordinates:

$X = -11.0, -9.5, -7.5, -5.5, 0.0$ (centre of the sphere), 5.5
$Y = -11.0, 11.0$

3. Irradiation conditions

The irradiation tests took place in the low-scatter irradiation room of PTB, using the PIAF accelerator [13]. The point of test, where the centre of SP^2 was located during irradiation, was located at approximately 88 cm from the neutron producing target (irradiation distance slightly changed when the beam changed). The neutron fluence rate at the point of test varied from approximately $5E+2$ cm^{-2} s^{-1} at 147 keV up to $8E+3$ cm^{-2} s^{-1} at 14.8 MeV and was known with uncertainty ranging from 2% to 4%. The width of the energy distribution from the neutron-emitting target, expressed in terms of *FWHM*, was approximately 17% at 147 keV, 8% at 1.2 MeV and less than 4% at other energies. The fraction of target-scattered neutrons was 3% or lower.

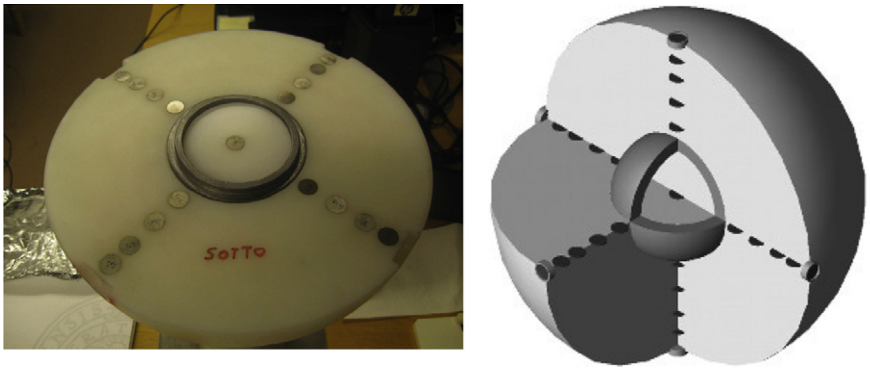

Fig. 1. The SP^2 neutron spectrometer. Left: the prototype (lower emi-sphere) with the Dy activation foils and the lower part of the lead shell. Right: the Monte Carlo model showing the arrangement of the measurement positions along three perpendicular axis, as well as the inner lead shell.

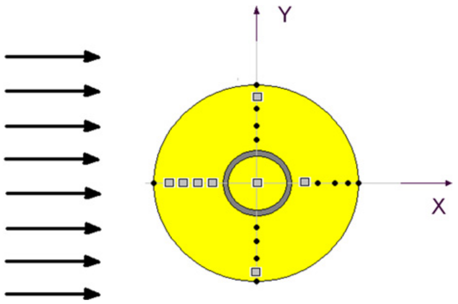

Fig. 2. Sketch of the adopted mono-directional irradiation goemetry. A cut view of the sphere on the $Z=0$ plane is shown. The measurement positions used in the experiment are the grey squares. Black dots are non-used measurement positions. Positions along the Z axis are not visible.

Because the accelerator current slightly varied during the irradiation, the value of accelerated charge integrated each minute was used for normalization purposes. The specific activity on the Dy foils was corrected by taking into account this variability. The correction procedure is described in Ref. [14].

The shadow-cone technique could not be used because of the rather short irradiation distance, required to achieve measurable activation in the foils. Consequently the spectrometer was exposed to the sum of the direct field from the target plus the field scattered from the air and the holding structures. Additional simulations were performed to evaluate the effect of the air and of the structures (metallic stands and grating floor) in the SP^2 simulated response, but only the surface measurement positions (radial distance from centre=12.5 cm) were affected. These positions are not of interest for this work.

4. Results of the irradiation tests

For every monoenergetic energy, eight activation foils were simultaneously exposed in the measurement points evidenced in Fig. 2. The $F_{i,E}$ values experimentally obtained are reported in Table 1 for every mono-chromatic energy and for the selected measurement positions.

Uncertainties on the single $F_{i,E}$ values vary from ±4% to ±7%, due to:

- the counting uncertainty (±2% to ±6%, depending on the beam intensity and on the foil position within the sphere), which also includes a ±2% contribution to account for the reproducibility of the beta counting and of the foil position inside the reader [15];
- the uncertainty on the reference fluence rate at the point of test (±2% to ±4%, depending on the beam energy); and
- the uncertainty on the distance from the target and the SP^2 (±1%).

Considering each monochromatic irradiation as a separate experiment, a best estimation of the calibration factor, F_E, was derived for every energy (see last line of Table 1). Taking uncertainties (±3% to ±5%) into account, the different values of F_E are in agreement. The global calibration factor, F, was then obtained by a weighted average of the F_E values, using the inverse square of uncertainty as weighting factor. Its numerical value is $F=0.134\pm0.002$. The variability of F_E, as the beam energy changes, is ±3% (one standard deviation), which may be considered as the “overall uncertainty” of the simulated response matrix.

If the experimental count rate C_i is studied along the X-axis, the profiles of Figs. 3–7 are obtained for the different beam energies. The experimental count rate is compared with the “expected” count rate, i.e. that obtained from the product Ff_i^{100}. The uncertainty bar on the “expected” count rate is the quadratic combination of the reference fluence rate uncertainty (±2% to ±4%, depending on beam energy) and of the response matrix overall uncertainty, now estimated to be ±3%. From these plots 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 maximum of the profile shifts toward deeper positions as the energy increases. This effect, which constitutes the basis for using SP^2 as a neutron spectrometer, is evidenced in Fig. 8. Here the different profiles are compared after normalization to their maximum.

5. Conclusions

A prototypal neutron spectrometer, called SP^2 (SPherical SPectrometer), was designed in the framework of the INFN project NESCOFI@BTF. It consists of 31 thermal neutron detectors embedded in a 25 cm diameter polyethylene sphere with an internal 1 cm thick lead shell. The final objective of NESCOFI@BTF is to equip this moderator with active thermal neutron detectors, thus resulting in a real-time spectrometric monitor. Relevant properties of SP^2 are the isotropic response from the thermal domain up to hundreds of MeV neutrons and the ability to determine the whole spectrum in only one exposure. According to the theoretical design, published in a previous work [2], the expected spectrometric performance is similar to that of the extended range Bonner sphere spectrometer. However, before developing the final active instrument, an experiment was needed to

Table 1
Value of $F_{i,E}$, obtained for every mono-chromatic energy and for the eight selected measurement positions. Uncertainties ranges from $\pm 4\%$ to $\pm 7\%$.

	147 keV	565 keV	1.2 MeV	5.0 MeV	14.8 MeV
$X=-11.0$	0.131	0.138	0.148	0.134	0.135
$X=-9.5$	0.130	0.139	0.145	0.135	0.132
$X=-7.5$	0.129	0.138	0.144	0.133	0.132
$X=-5.5$	0.130	0.133	0.138	0.131	0.127
$X=0$	0.128	0.134	0.127	0.128	0.125
$X=5.5$	0.123	0.132	0.128	0.125	0.125
$Y=-11.0$	0.137	0.148	0.138	0.132	0.143
$Y=11.0$	0.139	0.138	0.146	0.141	0.142
F_E	0.130 ± 0.004	0.137 ± 0.004	0.138 ± 0.005	0.132 ± 0.004	0.131 ± 0.006

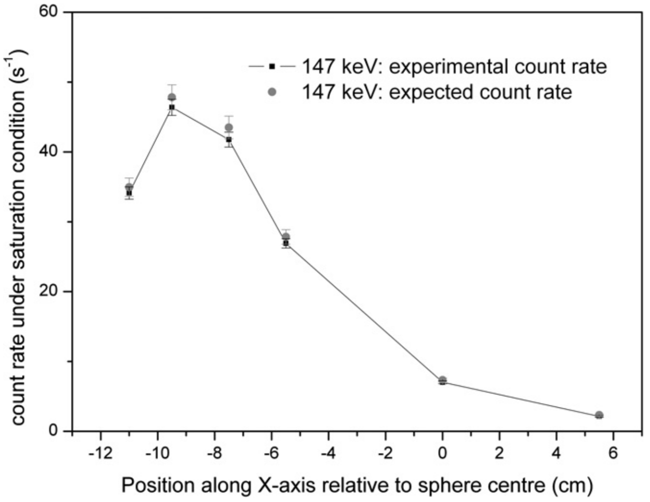

Fig. 3. Saturation count rate measured in the Dysprosium activation foils exposed in the selected positions of SP^2 for the 147 keV mono-chromatic beam. The expected count rate, obtained from the simulated response matrix, is also reported. Lines are only eye guide.

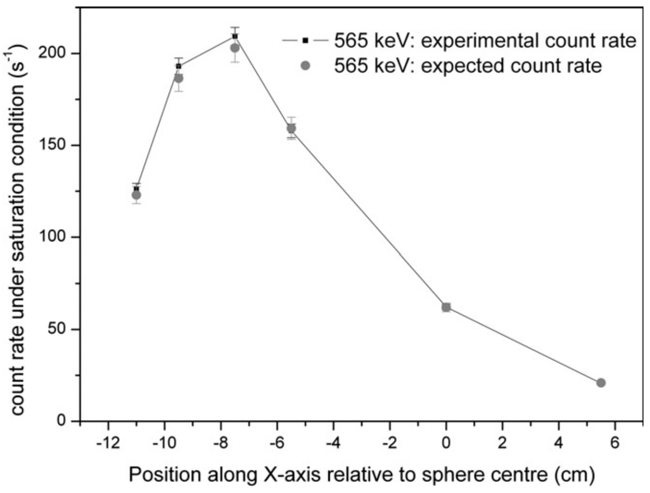

Fig. 4. Saturation count rate measured in the Dysprosium activation foils exposed in the selected positions of SP^2 for the 565 keV mono-chromatic beam. The expected count rate, obtained from the simulated response matrix, is also reported. Lines are only eye guide.

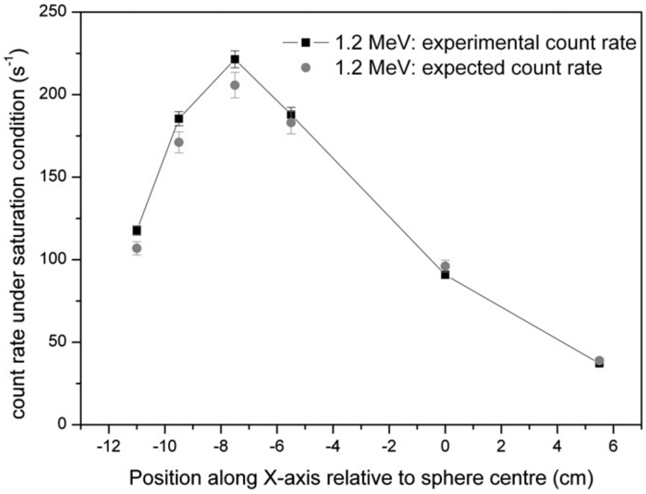

Fig. 5. Saturation count rate measured in the Dysprosium activation foils exposed in the selected positions of SP^2 for the 1.2 MeV mono-chromatic beam. The expected count rate, obtained from the simulated response matrix, is also reported. Lines are only eye guide.

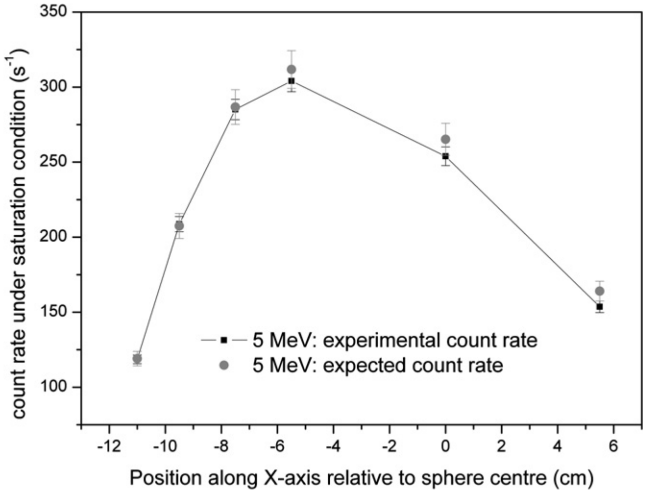

Fig. 6. Saturation count rate measured in the Dysprosium activation foils exposed in the selected positions of SP^2 for the 5 MeV mono-chromatic beam. The expected count rate, obtained from the simulated response matrix, is also reported. Lines are only eye guide.

verify the correctness of the simulated response matrix. A simplified prototype was produced and equipped with Dysprosium activation foils. This device was exposed in reference monochromatic neutron fields from 147 keV up to 14.8 MeV at PTB Braunschweig. The experiment allowed concluding that the simulated response matrix is able to predict the spectrometer experimental response within $\pm 3\%$ in the studied energy range, thus opening the way to the production of an active version of the instrument. The active SP^2 could be conveniently used, in a variety of neutron producing facilities, to control on-line the neutron production in terms of both intensity and energy distribution.

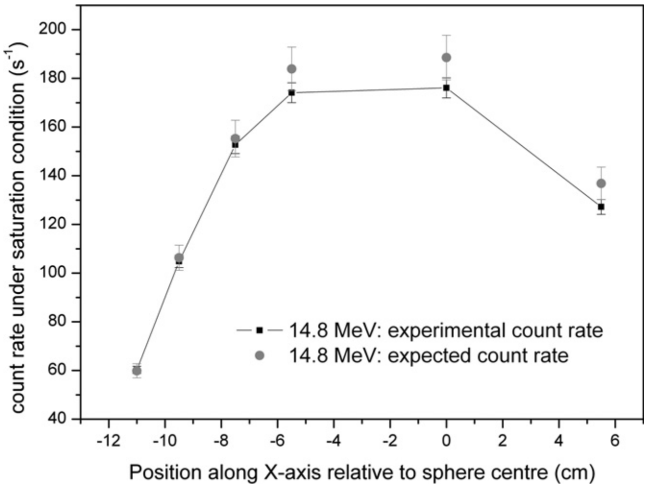

Fig. 7. Saturation count rate measured in the Dysprosium activation foils exposed in the selected positions of SP^2 for the 14.8 MeV mono-chromatic beam. The expected count rate, obtained from the simulated response matrix, is also reported. Lines are only eye guide.

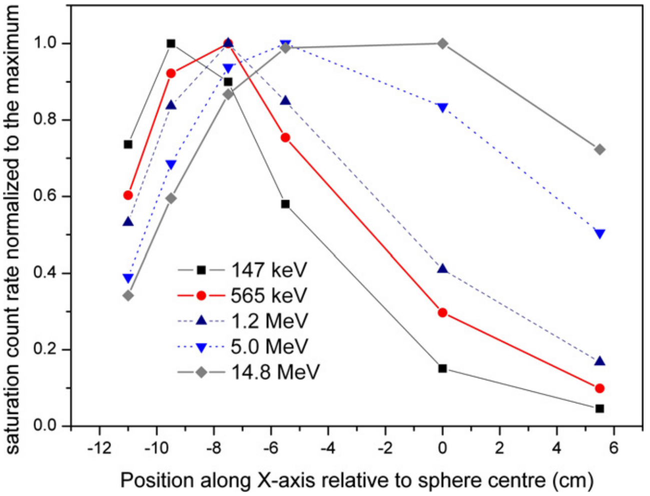

Fig. 8. Experimental profile of the saturation count rate along the *X*-axis for different mono-chromatic beams. Each profile is normalized to its maximum. Lines are only eye guide.

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