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First test of SP^2: A novel active neutron spectrometer condensing the functionality of Bonner spheres in a single moderator

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ABSTRACT

The NESCOFI@BTF (2011–2013) international collaboration was established to develop realtime neutron spectrometers to simultaneously cover all energy components of neutron fields, from thermal up to hundreds MeV. This communication concerns a new spherical spectrometer, called SP\widehat2, which condenses the functionality of an Extended Range Bonner Sphere Spectrometer (ERBSS) into a single moderator embedding multiple active thermal neutron detectors. The possibility of achieving the complete spectrometric information in a single exposure constitutes a great advantage compared to the ERBSS. The first experimental test of the instrument, performed with a reference 241Am–Be source in different irradiation geometries, is described. The agreement between observed and simulated response is satisfactory for all tested geometries.

1. Introduction

The NESCOFI@BTF (2011–2013) international collaboration was established with the aim of developing real-time neutron spectrometers to simultaneously cover all energy components of neutron fields, from thermal up to hundreds MeV. The final users of these instruments will be neutron-producing facilities, ranging from medical to industrial and research fields. The basic idea is to condense the functionality of an Extended Range Bonner Sphere Spectrometer (ERBSS) [1] into a single moderator embedding multiple active thermal neutron detectors. The expected performance, in terms of accuracy and spectrometric capability, are those of the ERBSS. However, the possibility of achieving the complete spectrometric information in a single exposure constitutes a great advantage compared to ERBSS. The project proposed to develop two different spectrometers:

– CYSP (CYlindrical SPectrometer), with unidirectional response [2];
– SP^2 (SPherical SPectrometer), with isotropic response.

This paper is focused on the SP^2. The spectrometer was designed through an extensive Monte Carlo simulation campaign with the MCNPX 2.6 [3] code that allowed optimizing the radius of the spherical polyethylene moderator, the internal distribution of the thermal neutron detectors and the thickness and location of an internal lead shell for enhancing the high-energy response. The final design consists of a 25 cm diameter polyethylene sphere embedding 31 thermal neutron detectors arranged in symmetrical positions along the three axes. The internal one cm thick lead shell, acting as (n, xn) degrader, allows extending the energy interval of the response up to hundreds of MeV [4]. The SP^2 response matrix is fully known by Monte Carlo simulation. The average reading of the six detectors located at the same radial position proved to be nearly independent from the irradiation geometry, thus constituting an isotropic data, which is only function of the radial position and the neutron energy. This is the basis for using SP^2 as a spectrometer [4].

According to this theoretical design, a passive prototype equipped with Dysprosium activation foils was built, in order to experimentally validate the simulated response matrix. The device was irradiated with quasi-monoenergetic reference neutron fields from 147 keV to 14.8 MeV available at PTB Braunschweig. This campaign allowed estimating in $\pm 3\%$ the overall uncertainty of the simulated SP^2 response matrix, for the investigated energy range [5].

A further stage was the development of customized active thermal neutron detectors fulfilling the following characteristics:

(1) miniaturization (the target dimension for a single detector is in the order of 1 cm);

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(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 thirty-one detectors, thus excluding for budget reasons practically all commercially available active detectors).

Among the two solid-state devices developed by the project [6,7], the TNPD type (thermal neutron pulse detector) was used in this work. The TNPD produces a pulse-height distribution from which the thermal neutron fluence is derived. Typical thermal neutron sensitivity is 0.03 cm^2 (counts per unit fluence) [7].

This work presents a first test of the SP^2, equipped with TNPD active detectors, in different irradiation geometries, using a reference source of ^{241}Am–Be (strength 2.09E+6 s^{-1}) available at INFN-LNF calibration laboratory.

2. Measurement set-up

To study the spectrometer response as a function of the irradiation geometry, the SP^2 was equipped with a single "radius" of five detectors occupying radial positions 0.0 cm (centre), 5.5 cm, 7.5 cm, 9.5 cm and 11 cm. The shallowest position at $R=12.35$ cm, corresponding to an un-moderated detector to measure thermal neutrons present in the incident field, was not used, because no thermal neutrons are present in the Am–Be spectrum. The orientation of the spectrometer with respect to the Am–Be source was then changed in order to achieve the different irradiation geometries (1 0 0), (−1 0 0), (0 1 0), (0 −1 0), (0 0 1) and (0 0 −1) (see Fig. 1). The results from the last four symmetrical geometries were averaged and referred as a single "lateral" geometry (LAT).

The difference in sensitivity among different TNPDs was accounted by introducing individual correction factors, previously determined by exposing every TNPD in the same thermal neutron field as explained in Ref. [7]. This correction allows reducing to about ±3% the detector-to-detector response variability.

A dedicated multi-detector analog compact board was developed to acquire the signals from the multiple detectors of the SP^2. The board includes eight analog channels, each formed by a bias regulator, a charge preamplifier and a shaper amplifier. The eight amplified analog signals are sent to a commercial digitizer programmed within the LabView environment. This allows to simultaneously acquire on a PC the pulse height spectra from all TNPDs.

For every irradiation geometry the Am–Be source was placed at 1 m from the SP^2 center (point of test). The shadow-cone technique was adopted to account for the room- and air- scattered component of the neutron field, so that twelve exposures were performed in total.

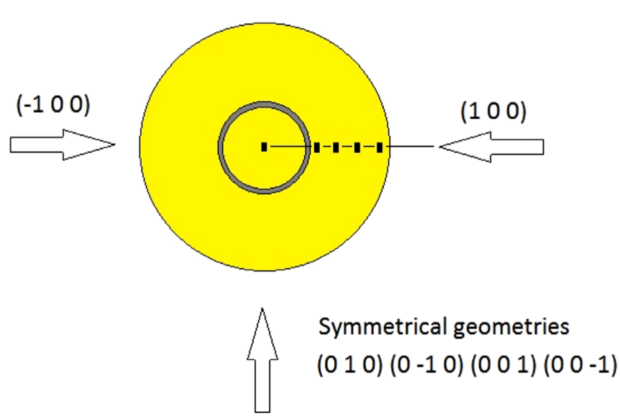

Fig. 1. Irradiation geometries chosen for the experiment. Cut-view of the SP^2 from top. (0 1 0), (0 −1 0), (0 0 1) and (0 0 −1) symmetrical geometries are grouped into a single "lateral" geometry, called LAT.

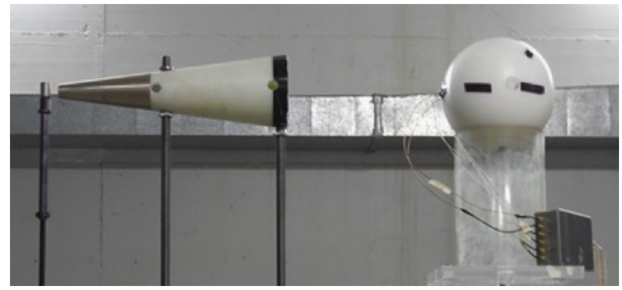

Fig. 2. Irradiation set-up for the "cone configuration". The source-to-cone distance was 3 cm, whilst the source-to-detector distance was 100 cm.

Fig. 2 shows the experimental set-up in the case of the (1 0 0) irradiation with the shadow-cone ("cone configuration").

The source-to-cone distance and the source-to-detector distance were equal to 3 cm and 100 cm, respectively.

3. Results

Fig. 3 shows the pulse height spectra from the five TNPDs for an exposure time of 54,000 s, in (1 0 0) geometry and in total-field condition (no shadow-cone). The initial portion of the spectra is influenced by the secondary electrons due to the moderation photons plus those present in the free-in-air-field. The broad peaked structure above 1 V is due to the charged particles produced by thermal neutrons in the converter covering the solid-state sensor. Previous optimization tests allowed fixing a photon-to-neutron discrimination threshold to 0.6 V, which corresponds to a local minimum in the spectra.

For a given geometry, the number of pulses in each detector integrated from 0.6 V to 3 V was normalized to the exposure time and corrected for the scattered radiation by subtracting the corresponding quantity obtained with the shadow-cone. This difference was corrected for the individual sensitivity of the TNPDs and normalized to the free-in-air neutron fluence rate at the point of test (sphere center). The resulting array represents the "observed" SP^2 count per unit fluence, symbolized with $C_g(R)$, where pedix "g" refers to the specific irradiation geometry and R is the radius corresponding to the detector position: $R=0.0$ cm (centre), 5.5 cm, 7.5 cm, 9.5 cm and 11 cm.

In parallel, the SP^2 response was calculated with MCNPX. The model includes accurate description of the SP^2 in terms of materials and densities. The simulations determined the number of thermal neutron capture reactions in the converter of the TNPD in different radial positions, per unit fluence from a ^{241}Am–Be source placed at 1 m from the sphere centre, in an ideal scatter-free scenario. The simulated number of capture reactions per unit fluence is termed $M_g(R)$. The ratio $F_g(R)=C_g(R)/M_g(R)$ represents the spectrometer calibration factor. If the Monte Carlo model well represents the real geometry, then the ratio $F_g(R)$ is constant as the irradiation geometry and the detector position change. Thus the accuracy of the simulation model can be quantified by the constancy of F. Table 1 shows $F_g(R)$ for different radial positions and geometries. Because the (0 1 0), (0 −1 0), (0 0 1) and (0 0 −1) geometries are symmetrical, they have averaged and reported as a single geometry (LAT, meaning "lateral"). Uncertainties of experimental values, in the order of 3% to 5%, are due to the residual detector-to-detector response variability and to the counting statistics. The values of $F_g(R)$ are less than 1 because not all charged particles generated in the converter produce a detectable signal.