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Comparing active and passive Bonner Sphere Spectrometers in the 2.5 MeV quasi mono-energetic neutron field of the ENEA Frascati Neutron Generator (FNG)

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ABSTRACT

Bonner Sphere Spectrometer (BSS) equipped with passive detectors are used to replace active BSS in radiation environment characterized by high fluence rate, large photon background and pulsed time structure as those encountered near particle accelerators. In this work a newly developed passive Bonner Sphere Spectrometer, using Dysprosium activation foils as central detectors (Dy-BSS), was tested through comparison with a well-established active BSS. As a suitable neutron field, where both systems can correctly operate, the 2.5 MeV quasi mono-energetic beam of the ENEA Frascati Neutron Generator (FNG) was chosen. The two spectrometers are based on substantially different operation principles, therefore their response matrix are very different. In addition, the BSS are independently calibrated in different reference neutron fields. The exercise took place at 90° and at a fixed distance from the neutron emitting deuterated target. As reference data, the results obtained by unfolding the active BSS data were used. The FRUIT unfolding code, ver. 5 was used.

The results of the Dy-BSS are fully comparable with those of the active BSS, in terms of both total fluence and shape of the neutron spectra. For the energy range studied in this exercise, the expected level of accuracy of the Dy-BSS and its suitability for operational neutron monitoring are fully confirmed.

1. Introduction

Active and passive Bonner Sphere Spectrometers (BSS) play complementary roles in the operational monitoring of neutron fields around neutron generating facilities (Alevra and Thomas, 2003). Active BSS employing ^{3}He or ^{6}LiI(Eu) counters have in general high neutron sensitivity. As an example, the response of the 8" sphere at 1 MeV ranges from 10^{-1} to 2–3 cm^{2}, depending on the type of active counter. However, their operation may be affected by saturation and dead time effects when the neutron fields are characterized by high fluence rate, pulsed time structure and large photon background. These conditions are routinely evident in accelerator-based facilities. Passive BSS based on activation foils are frequently used to replace active BSS in these radiation environments. Their sensitivity is lower than that of the active BSS, but they are suited to operate in pulsed fields. In addition their photon sensitivity is in most cases negligible. Gold foils are usually adopted as central detector for the passive BSS (Thomas et al., 2002), but their application is operatively limited to fluence rate higher than in the order of 10^{3}–10^{4} cm^{-2} s^{-1} (Garcia-Fusté, 2010). A new passive BSS based on Dysprosium activation foils (Dy-BSS) was recently developed at INFN-LNF (Bedogni et al., 2010, 2010a). The characteristics of the new system depends from the combination of the large thermal neutron cross-section of Dy (2700 barn at 0.025 eV) and the short half live of the activation products (2.334 h):

- Sensitivity for operational measurements: the specific activity obtained after irradiation of few minutes, representative of the short times allowed for dosimetry sessions in most operational conditions (e.g. medical LINACs) is a factor 200 higher than for gold foils;
- Capability to provide rapid results: the foils can be easily counted in situ with a portable beta counter.
- If all spheres are exposed at the same time and only one counter is available, the short half live of the activation products would constitute a limitation in the counting procedure.

With the aim of testing the Dy-BSS against a well-established active BSS, a measurement campaign was organized in the 2.5 MeV quasi mono-energetic field of the ENEA Frascati Neutron Generator (FNG). The neutron beam was obtained by bombarding

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a Ti-D target with 260 keV deuterons. Due to the small photon component and the possibility to vary the ion current, both active and passive spectrometers could correctly operate in this field.

The active BSS, previously validated in several well-known neutron fields, is based on a cylindrical 4 mm × 4 mm ^{6}LiI(Eu) scintillator. The active and the passive BSS rely on substantially different operation principles, therefore their response matrices are very different. In addition, the BSS have been independently calibrated in different reference neutron fields.

The exposures took place in the same point of test at 90° field from the D–D source. The reference data, i.e. the neutron fluence and the numerical spectrum in the point of test, were determined by unfolding the data from the active BSS with the version 5 of the FRUIT unfolding code (Bedogni et al., 2007). Since a detailed neutron spectrum calculated with the method described in Angelone et al. (1996) was available, the FRUIT code was used in "pure numerical mode" (no parametric models were used) and the simulated spectrum was used as "a priori" information. The same analysis was then performed with the Dy-BSS readings and the results were compared with the reference data.

2. The irradiation set-up

The experiment took place in the large low-scattering FNG irradiation room (about 20 m × 20 m × 20 m) at 90° from the deuterium target. The neutron beam was obtained by bombarding a Ti-D target with 260 keV deuterons. The flight-path of deuteron ions is located at approx. 10 m from the ground. Fig. 1 shows the scheme of the FNG accelerator and the location of the point of test. The active and the passive BSS were sequentially exposed at a fixed distance (66.6 cm) from the target. The neutron fluence rate ranged in the interval $4\cdot10^2$–$4\cdot10^3$ cm^{-2} s^{-1}. The neutron beam had no time structure, since it was produced by a continuous current of deuterium ions. A NE213 neutron scintillator located in the vicinity of the neutron emitting target was used as normalization instrument, therefore the reference data is expressed in terms of neutron fluence per unit NE213 count. The irradiation time was in the order of 2 min per sphere and 20 min per sphere for the active and passive BSS, respectively. The reproducibility of the irradiation condition was checked by a series of repeated exposures of the ^{6}LiI(Eu) active detector in the 8" sphere: the ratio between the ^{6}LiI(Eu) counts and the NE213 counts was found to be constant within ±1.2% standard deviation.

3. The active BSS

In this work only the spheres with significant response at 2.5 MeV were used: 5", 7", 8", 10" and 12". In addition, 3 spheres with extended energy range were used, namely 12" with 1 cm Pb internal layer [12(Pb)], 7" with 1.27 cm Pb internal layer [7"(Pb)] and 7" with 1.27 cm Cu internal layer [7"(Cu)]. Each extended range sphere is constituted by an internal PE (polyethylene) sphere surrounded by a metal layer and an external PE shell. The central thermal neutron detector is a cylindrical 4 mm × 4 mm ^{6}LiI(Eu). The active BSS is schematized in Fig. 2.

The response matrix, calculated with MCNPX (Waters, 2002) from $1.50\cdot10^{-9}$ MeV up to $1.16\cdot10^3$ MeV, was experimentally verified in reference radionuclide neutron fields (Bedogni, 2006) and in quasi mono-energetic beams (Bedogni et al., 2010b) and its overall uncertainty was estimated to be ±3%. The calibration factor, derived in the reference Am–Be field of INFN-LNF using the shadow-cone technique, is routinely checked using a fixed-geometry portable moderator with a 0.1 Ci Am–Be source in its center. The spectrometer calibration factor is known with ±1% uncertainty, accounting for the uncertainties due to the calibration process and that due to the counting repeatability of the central detector.

4. The Dy-BSS

The passive BSS, schematized in (Fig. 2), operates with the same set of spheres as the active BSS. In every exposure, a Dysprosium foil with diameter 12 mm, thickness 0.1 mm, and purity >99.9% is positioned in the sphere center through a specially designed polyethylene cylindrical holder with diameter 13 mm. Thermal and epithermal neutrons activate the ^{164}Dy isotope (28.2% abundance in natural Dysprosium) producing ^{165}Dy, a beta-gamma emitter with half-life 2.334 h. The main beta emission (83%) has end-point energy 1.287 MeV, whilst all significant photon emissions have energies lower than 53 keV. Due to its high energy and high yield, the beta emission is certainly the most suitable for in situ measurements. A commercial beta counter is used to count the foils after irradiation.

The response matrix of the Dy-BSS was calculated with MCNPX on the basis of a 68-groups energy equi-lethargy structure from $1.50\cdot10^{-9}$ MeV to $1.16\cdot10^3$ MeV (more details on the calculations are given in Bedogni et al. (2010)). A validation experiment performed in the ENEA Bologna ^{252}Cf reference field allowed estimating its overall uncertainty, in the energy range covered by that source, in ±2.3%.

The Dy-BSS response matrix is expressed in terms of saturation specific activity (or saturation count rate in the beta counter) per unit neutron fluence rate. The procedure needed to obtain this quantity from the result of the beta counting (Bedogni et al., 2010) implies corrections for (1) the detector efficiency, (2) the decay between the end of the irradiation and the beginning of the

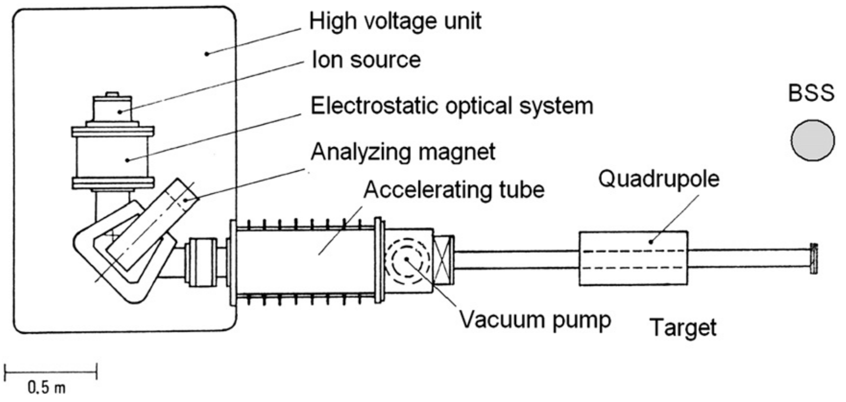

Fig. 1. Schematic diagram of the ENEA Frascati Neutron Generator (FNG). The label "BSS" identifies the point of test at 66.6 cm from the neutron-emitting target.

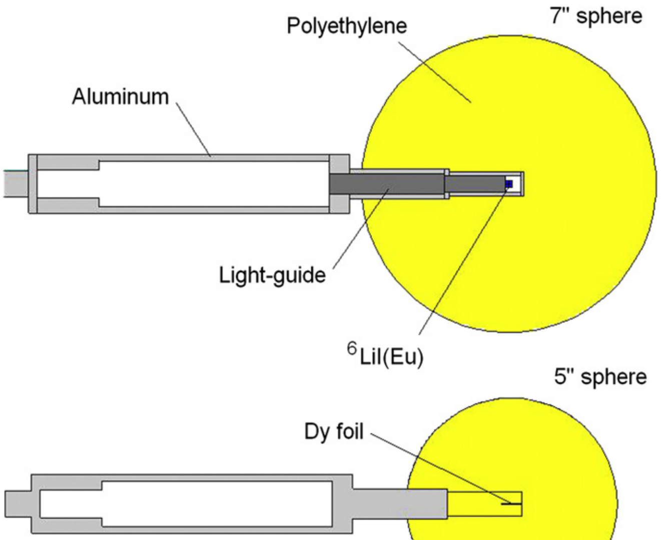

Fig. 2. Schematic diagrams of the active BSS (top) and the passive Dy-BSS (bottom).

measurement, (3) the decay during the measurement and (4) the fraction of the saturation activity reached during the irradiation. The last factor (saturation factor, F_{sat}) is given by Eq. (1) for constant rate sources:

$$F_{\text{sat}} = 1 - 2^{-\frac{t_{\text{irr}}}{T}} \tag{1}$$

Where t_{irr} is the irradiation time and T the half live of the isotope.

A more complex correction is needed for variable output facilities, as the FNG beam. In this case, the increase of the specific activity in the Dy foils during the irradiation was calculated based on the instantaneous value of the source intensity (step-by-step correction), which was assumed proportional to the count rate in the NE213 counter. The calculation was performed using a 3 s time step. Fig. 3 shows the typical time dependence of F_{sat}, correlated with the instantaneous beam intensity during the irradiation of a sphere. It is worth saying that the use Eq. (1) instead of the step-by-step correction could lead, in the condition of this study, to systematic errors in the order of 1%–2% in the determination of F_{sat}.

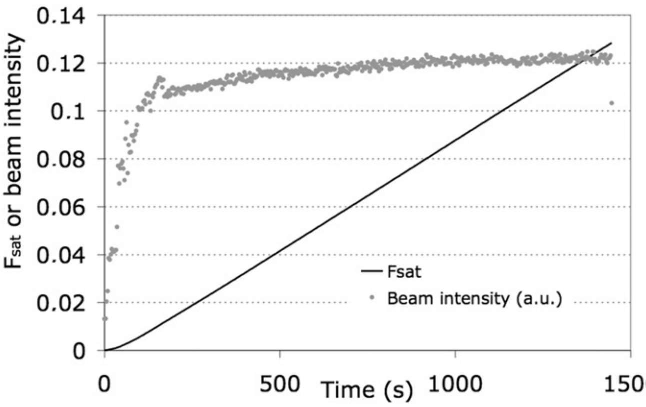

Fig. 3. Theoretical time dependence of F_{sat} and of the beam intensity during the irradiation of a sphere.

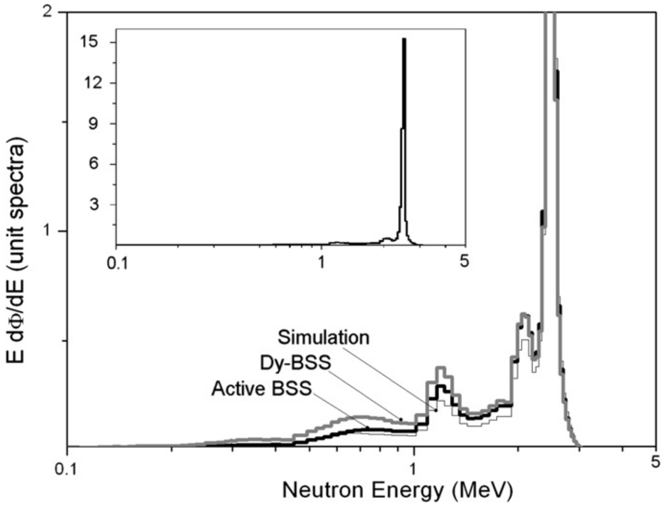

Fig. 4. Comparison between the unfolded spectra (active BSS and Dy-BSS) and the simulated spectrum using full Y scale (in the insert: in this scale all spectra appear identical) and a reduced Y scale. All spectra are normalized to unit fluence and in equilethargy representation.

5. Results and discussion

5.1. Reference data

For the active spectrometer the BSS counts (8 spheres) were normalized to the total number of NE213 counts acquired during the exposure and used as input data for the unfolding code. The associated uncertainties (σ_c) were assessed as the sum in quadrature of the following contributions: (1) the counting uncertainty of the ^{6}LiI(Eu) (<±0.4%) and of the NE213 counters (<±0.4%); (2) the time variability of the irradiation conditions, quantified ±1.2% (see Section 2) and (3) the overall uncertainty of the response matrix (±3%). The spectrum normalized to the unit fluence (unit spectrum) is shown in Fig. 4 together with the simulated spectrum. Other numerical results are reported in Table 1, particularly the peak energy, the neutron fluence per unit NE213 count and the value of the convergence indexes d_{max} and δ. These indexes express the coherence between the BSS counts and the unfolded spectrum and are defined as:

d_{max}: the maximum of the index d, defined for a given sphere as the difference between the experimental sphere reading and the reading obtained by folding the unfolded spectra with the BSS response matrix (called "folded reading"), normalized to the experimental reading.
δ: the average of d over all spheres

The uncertainty of the neutron fluence (~1.5%) is the quadratic combination of the BSS calibration uncertainty (1%) and of the unfolding uncertainty. The unfolding uncertainty is the result of the propagation of the BSS counts uncertainties, σ_c, through the unfolding procedure. This propagation is done by randomly generating a large number (10^3) of sets of BSS counts, using σ_c as

Table 1
Convergence parameters, peak energy and total neutron fluence obtained by unfolding the active and passive BSS data.

	Active BSS	Dy-BSS
d_{max}	3%	4%
δ	<1%	1%
E_{peak}(MeV)	2.5 ± 0.2	2.5 ± 0.2
φ (cm^{-2})	28.4 ± 0.4	27.8 ± 0.7

amplitude of the Gaussian perturbation, then separately unfolding each set. The uncertainties are obtained from the distribution of the results.

The low values of $d_{\max}$ and δ and the similarity between the unfolded and the simulated spectra (See Fig. 4) indicate good coherence between the experimental data and the simulated spectrum.

5.2. Dy-BSS results

For the passive spectrometer the following normalization procedure was adopted. Since the response function of the Dy-BSS is defined as the saturation specific activity (or saturation count rate in the detector) per unit fluence rate, and the fluence rate in the measurement point was proportional to the NE213 count rate which varied with time, a “reference” value of the NE213 count rate was established (reference intensity, Y_{ref} (s^{-1})). Using the step-by-step correction algorithm mentioned in Section 4, the count rate of each foil was corrected to obtain the saturation count rate in condition of reference intensity. The corrected specific activities (As_i, where i identifies the sphere) are used as input data for the unfolding code, and the unfolding process provides (among other data) the fluence rate corresponding to the reference intensity. This value divided by Y_{ref} provides the fluence per unit NE213 counts, which is directly comparable with the reference data measured with the active BSS. The sum in quadrature of the following contribution were used as uncertainties of the input data for the unfolding code, σ_c: (1) the counting uncertainties of the beta counter (<±0.9%) and of the NE213 (<±0.4%) counter; (2) the variability of the irradiation conditions (±1.2%) and (3) the uncertainty of the response matrix (±2.3%).

The unit spectrum is also shown in Fig. 4. The best estimation of the neutron fluence, the unfolded peak energy and convergence parameters are reported in Table 1. The uncertainty in the fluence is the quadratic combination of the unfolding uncertainty and of the Dy-BSS calibration uncertainty (<2.5%). The unfolding uncertainty is the result of the propagation of the BSS counts uncertainties, σ_c, through the unfolding procedure. This propagation is done by randomly generating a large number (10^3) of sets of BSS counts, using σ_c as amplitude of the gaussian perturbation, then separately unfolding each set. The uncertainties are obtained from the distribution of the results.

The Dy-BSS calibration uncertainty (<2.5%) mainly depends from the uncertainty of the emission rate of the ^{252}Cf reference source (2%) used in the validation experiment of the spectrometer (Bedogni et al., 2010).

The results obtained with the Dy-BSS are coherent with the reference data (active BSS). Particularly, the value of the neutron fluence differs from the reference value by about 2%, which confirms the expected level of accuracy of the Dy-BSS.

Another way to demonstrate the coherence of the Dy-BSS unfolded spectrum with the reference data is to calculate the neutron fluence from each single sphere of the Dy-BSS and compare it with the reference fluence. This is done in Fig. 5, where Eq. (2) is applied.

$$\phi_i = \frac{As_i}{Y_{\mathrm{ref}} \cdot \int \mathrm{d}E \cdot R_i(E) \cdot \varphi(E)} \tag{2}$$

$R_i(E)$ is the response function of the i-th sphere and $\phi(E)$ the unfolded spectrum normalized to the unit fluence.

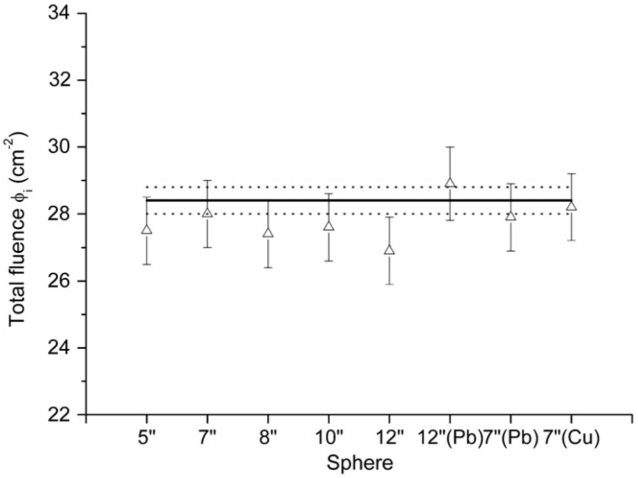

Fig. 5. Determination of the fluence from every sphere of the Dy-BSS. Error bars (±one sigma) are about ±3.5%. The lines represent the reference fluence, determined with the active BSS, and its variability range (±one sigma).

6. Conclusions

The passive BSS based on Dy activation foils was tested through comparison with a well-established active BSS in the 2.5 MeV quasi mono-energetic neutron field of FNG (ENEA Frascati). The data were unfolded with the FRUIT unfolding code, ver. 5, using a detailed simulated spectrum as “a priori information”. Both the neutron spectrum and the total fluence measured with the Dy-BSS agree with the reference data measured with the active BSS, within very limited uncertainties (about 2% for the total fluence). This test confirms the expected level of accuracy of the Dy-BSS response matrix and the suitability of this spectrometer for operational neutron monitoring.

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