Neutron Spectrometry Using LNL Bonner Spheres and FLUKA

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Abstract. The characterization of neutron fields has been made with a system based on a scintillation detector and multiple moderating spheres. The system, together with the unfolding procedure, have been tested in quasi-monochromatic neutron energy fields and in complex, mixed, cyclotron based environments. FLUKA simulations have been used to produce response functions and reference energy spectra.

Keywords: Neutron spectrometry; Bonner Spheres; Monte Carlo simulations.
PACS: 29.30.Hs; 24.10.Lx

INTRODUCTION

Neutron spectrometry based on multispheres system (Bonner Spheres System) is commonly used by many laboratories because of its almost isotropic response, wide energy range and easy operational approach. The LNL Bonner Sphere Spectrometer, based on a ^{6}LiI(Eu) scintillator and 7 moderating spheres, coupled to the unfolding code FRUIT 6.0 [1] (providing response functions calculated with the Monte Carlo code FLUKA [2] and [3]) was used to achieve neutron spectra generated by the interaction of protons of various energies with suitable targets. The CN Van de Graaff accelerator of the LNL can deliver up to 7 MeV protons, meanwhile the JRC Ispra cyclotron covers the range up to 40 MeV. At all irradiations, corrections of the backscattered neutrons were made using appropriate shadow cones. Using the FLUKA code, reference neutron spectra have been obtained in realistic irradiation conditions. These spectra and those obtained by the unfolding procedure have been compared. All spectra are reproduced at 0° angle. Neutron ambient dose equivalent has been evaluated, as well, using FLUKA and FRUIT and also measured using a portable rem counter.

OVERVIEW

Instrumentation

The LNL Bonner Sphere System is the commercially available Ludlum Model 42-5, from Ludlum Measurements, Inc [4].

The detector consists of a 4mm x 4mm ^{6}LiI(Eu) enriched crystal, coupled to a 1 ½ inch photomultiplier tube, used with the Ludlum Meas. Scaler Ratemeter.

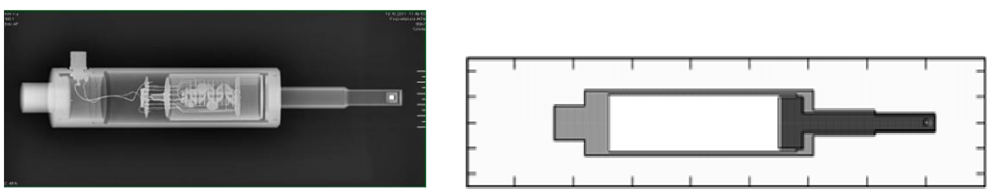
The unit is designed so that the center of the crystal is positioned in the center of the moderator spheres. The system is provided with 2”, 3”, 5”, 8”, 10” and 12” diameter spheres, of high density polyethylene, able to measure neutrons in the energy range 10^{-2}-10^{7} eV. An additional sphere has been manufactured, with lead and Cadmium layers, in order to extend the measures range up to 10^{9} eV [5].

Response Functions

The response functions used to unfold the counts of the spheres have been calculated with FLUKA. Each sphere has its own curve, representing the response in terms of detector counts per neutron unit fluence, as function of the incident neutron energy.

Since the detector signal is produced by the charged particles emerging in the $^{6}Li(n,\alpha)^{3}H$ reaction, the counts have been estimated in the simulation as the number of ^{3}H atoms in the scintillator volume. Those counts have been recorded through an estimator purposely set to score the residual nuclei produced in inelastic interactions.

In order to allow a simulation as close as possible to reality, the detector has been radiographed (FIGURE 1) and the geometry edited accordingly.



(a) (b)

FIGURE 1. (a): X-Ray radiography of the detector probe; (b) geometry used in FLUKA simulations.

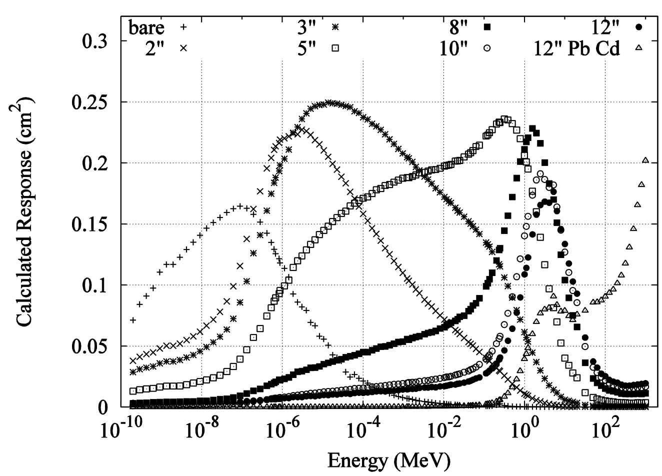


FIGURE 2. Response functions for the moderating spheres plus the bare detector, as simulated with the FLUKA code.

The neutron beam has been defined customizing the cross section of the beam spot to the appropriate sphere size.

For each configuration – 7 moderating spheres plus the bare detector – the response curve consists of an energy dependent interpolation of 120 points, in the range 10^{-5}-10^{9} eV (fig. 2).

Measurements

The 8 configurations – 7 moderating spheres plus the bare detector – have been exposed to the neutron field generated by LiF(p,n) and SiC(p,n) reactions.

At the CN Van De Graaff accelerator of the LNL, the 700 μg/cm^2 ^{7}LiF target (evaporation on a graphite backing) has been irradiated with proton of energies 2.3, 3.8 and 5.7 MeV. At the cyclotron of the JRC at Ispra, a 2 mm long ^{7}LiF target sintered with graphite to form a thick target has been irradiated with 30 and 35 MeV, while a thick SiC sintered target has been irradiated with 39 MeV protons. In the thick targets all the beam was stopped within the target.

In order to characterize the neutron field generated by the reactions of protons with the targets, the scattered radiation has been subtracted using appropriate shadow cones in dedicated measurements.

Unfolding Procedure

The unfolding of the sphere counts has been done using the FRUIT tool. In order to derive a physically acceptable solution, additional suggestions are needed, concerning the type of neutron field under investigation. In general, when a quasi-monochromatic beam was expected the physical model was a peak at the energy of the neutron beam. In presence of a cyclotron mixed neutron field, the model was fission.

Results

Protons of 2.3 MeV on ^{7}LiF thick target (700 μg/cm^2)

The interaction of protons of 2.3 MeV energy yields quasi-monoenergetic neutrons of 0.57 MeV in the forward direction. Figure 3 shows the unfolded BSS spectrum compared with the reference (FLUKA) one.

The neutron energy measured with the spheres is in good agreement with the theoretical value. The neutron energy spectrum calculated with FLUKA is slightly broader, since the full slowed down spectrum is reproduced in the simulation.

The ambient dose equivalent has been calculated folding the fluence with the fluence-to-dose conversion factors of the ICRP. The direct measure with the Rem Counter confirms the values found, as shown in table 1, first column.

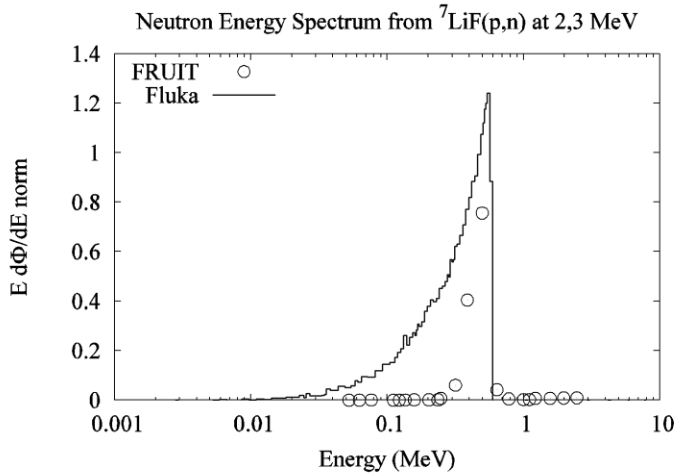


FIGURE 3. Neutron energy spectrum as obtained from the BSS (circles) and from the FLUKA code (solid line) with a proton beam of energy 2.3 MeV.

TABLE 1. Ambient dose equivalent per charge unit with 2.3, 3.8 and 5.7 MeV protons on LiF target as calculated with FLUKA, the BSS unfolding with FRUIT and the direct measure with the Rem Counter.

	H*(10) (μSv/μC)		
	2.3 MeV	**3.8 MeV**	**5.7 MeV**
FLUKA Simulation	0.04	0.4	1.3
FRUIT Unfolding	0.07	0.1	0.1
Rem Counter Measure	0.06	0.1	0.1

Protons of 3.8 MeV on ^{7}LiF thick target (700 μg/cm^{2})

A neutron spectrum peaked at 2.12 MeV in the forward direction is expected when a proton beam of 3.8 MeV energy impinges on a LiF target. This shape can be confirmed by the results shown in fig. 4

While the spheres unfolding yields a net peak around the neutron energy of 2.12 MeV, the FLUKA spectrum shows a complex double peaked distribution. This depends on the cross section of the materials, other than lithium, used in the simulation, and still to be investigated.

The ambient dose equivalent calculated by FRUIT is the same obtained with the direct measure using the rem counter, see table 1, second column.

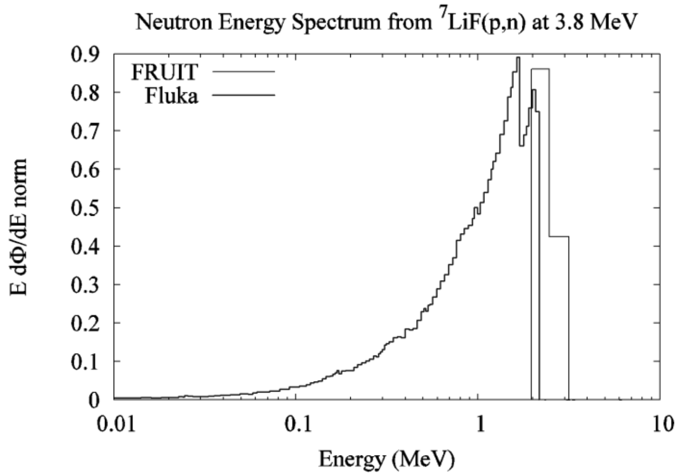


FIGURE 4. Neutron energy spectrum as obtained from the BSS (2 points solid line) and from the FLUKA code (complex spectrum) with a proton beam of energy 3.8 MeV.

Protons of 5.7 MeV on ^{7}LiF thick target (700 μg/cm^{2})

The reaction of protons with LiF at 5.7 MeV yields neutron of 4 MeV energy. The peak shift in figure 4 is mainly due to the energy defined in the response matrix. Being the expected energy not exactly defined in the response matrix, the peak is placed in its vicinity in the FRUIT convergence process.

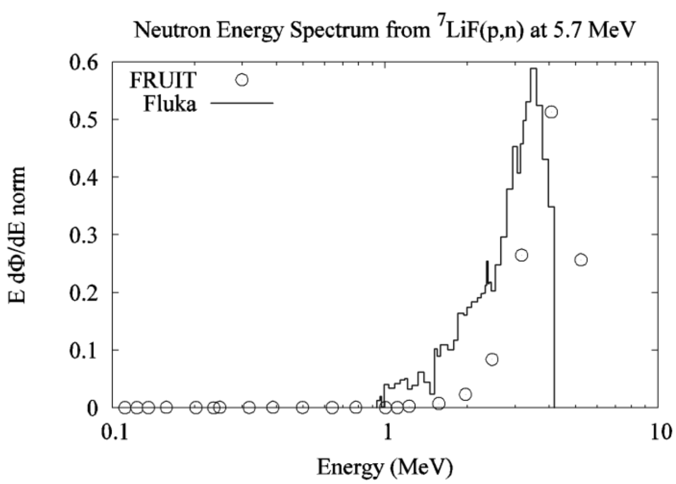


FIGURE 5. Neutron energy spectrum as obtained from the BSS (circles) and from the FLUKA code (solid line) with a proton beam of energy 5.7 MeV.

The ambient dose equivalent calculated with FLUKA is more than a factor 10 higher than the direct measures. This depends on the fact that the scattered field has not been subtracted (not visible in fig. 4 because it mainly consists of low energy neutrons) and it contributes significantly to the dose evaluation. The measures with BSS and the rem counter show a perfect agreement, as shown in table 1, column 3.

Protons of 30 MeV on ^{7}LiF thick target (2 mm)

At the JRC Ispra cyclotron, the neutron field has been characterized in the range 30-39 MeV proton energy on target. At first the irradiation of the ^{7}LiF target with 30 MeV protons was investigated.

The physical model used in the unfolding procedure has been “fission”, the only reasonable selection given for these energies by FRUIT 6.0 unfolding code.

The BSS measures do not allow a fine description of the structures in the intermediate energy region, but still a good agreement with the reference neutron spectrum was obtained. In any case the neutrons produced from the interaction of the energy degraded proton beam, escaping from the ^{7}LiF target, with the graphite backing is well reproduced.

The ambient dose equivalent calculated by FRUIT is in very good agreement with the direct measure using the rem counter.

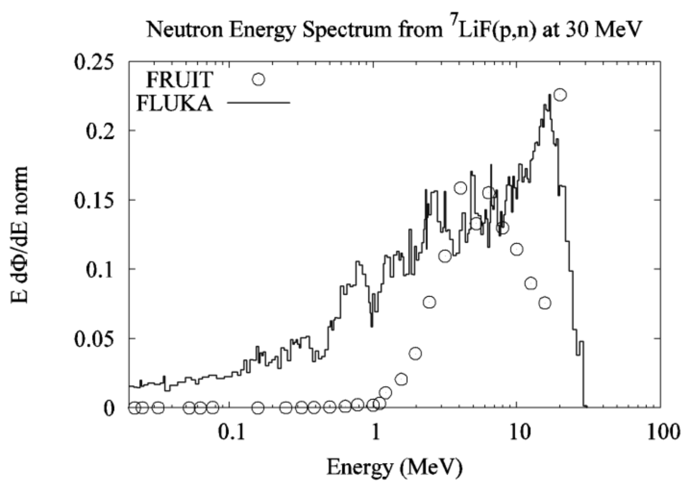


FIGURE 6. Neutron energy spectrum as obtained from the BSS (circles) and from the FLUKA code (solid line) with a proton beam of energy 30 MeV.

TABLE 2. Ambient dose equivalent per charge unit with 30 MeV protons on LiF target as calculated with FLUKA, the BSS unfolding with FRUIT and the direct measure with the Rem Counter.

	H*(10) (μSv/μC)
FLUKA Simulation	31.6
FRUIT Unfolding	22.3
Rem Counter Measure	20.4

Protons of 35 MeV on ^{7}LiF thick target (2 mm)

The peak energy neutron spectrum obtained by the BBS using FRUIT is in very good agreement with the reference quasi monoenergetic neutrons expected from the reaction at this energy and close to the spectra simulated by FLUKA.

The loss of some structures of the spectrum with the BSS at energies above 1 MeV is clear observing figure 7. The ambient dose equivalent measured with the rem counter is in good agreement with the value obtained by the simulation with FLUKA.

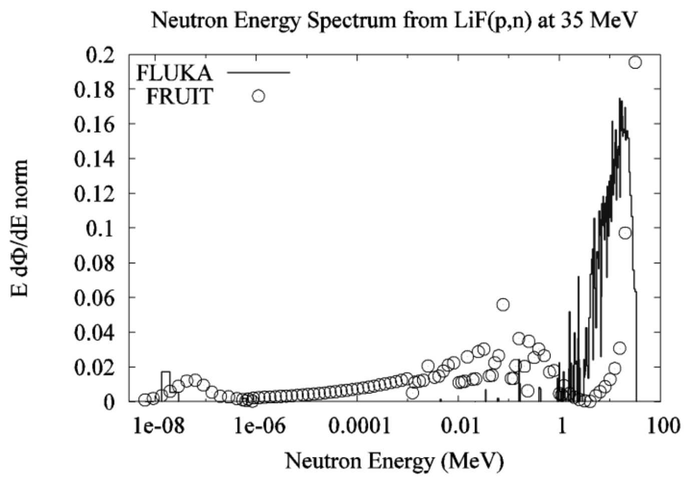


FIGURE 7 Neutron energy spectrum as obtained from the BSS (circles) and from the FLUKA code (solid line) with a proton beam of energy 35 MeV.

TABLE 3. Ambient dose equivalent per charge unit with 35 MeV protons on LiF target as calculated with FLUKA, the BSS unfolding with FRUIT and the direct measure with the Rem Counter.

	H*(10) (μSv/μC)
FLUKA Simulation	37.8
FRUIT Unfolding	53.7
Rem Counter Measure	30.4

Protons of 39 MeV on sintered SiC thick target

The energy spectrum obtained with the reaction of the proton beam with the SiC target ranges from thermal energies to about 20 MeV, as confirmed by the simulations.

As shown in the comparison of figure 8, with the BSS some structures are lost, and the spectrum looks smooth. Due to this loss of information at intermediate energies, the ambient dose equivalent is much lower than the simulation and the measure with rem counter. In fact the fluence-to-dose conversion factors are very high at the energy of interest.

TABLE 4. Ambient dose equivalent per charge unit with 39 MeV protons on SiC target as calculated with FLUKA, the BSS unfolding with FRUIT and the direct measure with the Rem Counter.

	H*(10) (μSv/μC)
FLUKA Simulation	18.2
FRUIT Unfolding	7.5
Rem Counter Measure	20.8

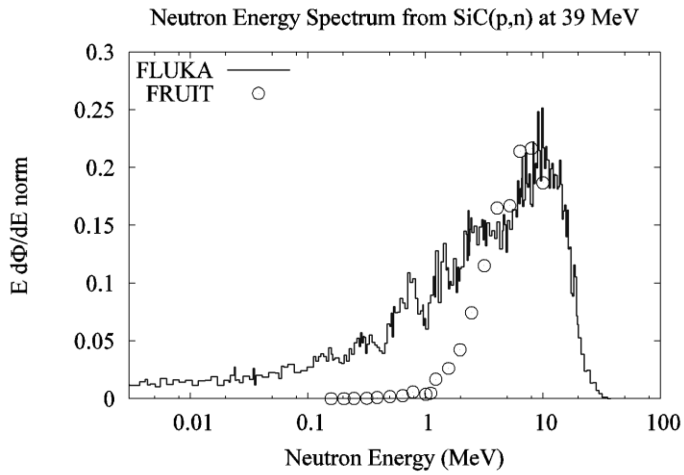


FIGURE 8. Neutron energy spectrum as obtained from the BSS (circles) and from the FLUKA code (solid line) with a proton beam of energy 39 MeV.

SUMMARY

A BSS using FRUIT, with FLUKA response functions, as unfolding code gives reliable responses for the measurement of workplace spectra aimed at neutron dose assessment. The neutron spectra obtained unfolding the sphere's readings, in particular with monoenergetic neutrons, is in good agreement with those obtained with FLUKA, which simulated the real experimental set up. Both reproduce quite well the expected spectra. Neutron H*(10) comparison shows - up to 30 MeV proton energy - a very good agreement (in the order of 15%) between FRUIT and direct measurement. At higher energies investigated, significant errors are due to poor a priori information and bad resolution of the response functions in the considered energy range.

ACKNOWLEDGMENTS

We would like to acknowledge all the personnel of LNL-CN accelerator and JRC's cyclotron for the help in the measurements set up, and Dr. Sara Carturan from the LNL for the preparation of the LiF targets.

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