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Calibration of a Bonner sphere extension (BSE) for high-energy neutron spectrometry

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Abstract

In a recent work, we constructed modular multisphere system which expands upon the design of an existing, commercially available Bonner sphere system by adding concentric shells of copper, tungsten, or lead. Our modular multisphere system is referred to as the Bonner Sphere Extension (BSE). The BSE was tested in a high energy neutron beam (thermal to 800 MeV) at Los Alamos Neutron Science Center and provided improvement in the measurement of the neutron spectrum in the energy regions above 20 MeV when compared to the standard BSS (Burgett, 2008 and Howell et al., 2009).

However, when the initial test of the system was carried-out at LANSCE, the BSE had not yet been calibrated. Therefore the objective of the present study was to perform calibration measurements. These calibration measurements were carried out using monoenergetic neutron ISO 8529-1 reference beams at the Physikalisch-Technische Bundesanstalt (PTB), Braunschweig, Germany. The following monoenergetic reference beams were used for these experiments: 14.8 MeV, 1.2 MeV, 565 keV, and 144 keV. Response functions for the BSE were calculated using the Monte Carlo N-Particle Code, eXtended (MCNPX). The percent difference between the measured and calculated responses was calculated for each sphere and energy. The difference between measured and calculated responses for individual spheres ranged between 7.9 % and 16.7 % and the arithmetic mean for all spheres was $(10.9 \pm 1.8) \%$. These sphere specific correction factors will be applied for all future measurements carried-out with the BSE.

Keywords

Extended range Bonner sphere; Bonner sphere; neutron spectrometry

1. Introduction

The Bonner Sphere Spectrometer (BSS) was first introduced in 1960 by Bramblett, Ewing and Bonner (1960). A typical system consists of a series of high-density polyethylene (PE) moderating spheres ranging from 5.08 cm to 30.48 cm (2-in to 12-in) in diameter with a thermal neutron detector placed at their centers. The BSS is a widely used neutron

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spectrometer because it responds over a very large energy range and has a nearly isotropic response (Thomas and Alevra, 2002). Above approximately 20 MeV however, the sensitivity of BSS decreases dramatically. Several research groups have investigated the use of high atomic number (Z) shells placed within polyethylene spheres to increase the high-energy sensitivity of the system, starting with the extended-range rem counter LINUS (Birattari et al., 1990, Birattari et al., 1992) followed by many others applying the method to BSS (Hsu et al., 1994, Birattari et al., 2000, Wiegel and Alevra, 2002, Mitaroff, 2002, Caresana et al., 2007, and Bedogni et al., 2007).

In a recent work, we constructed a cost effective modular multisphere system which expands upon the design of an existing, commercially available BSS by adding concentric shells of copper (Cu), tungsten (W), or lead (Pb). Our modular multisphere system is referred to as the Bonner Sphere Extension (BSE). The BSE was tested in a high energy neutron beam (thermal to 800 MeV) at Los Alamos Neutron Science Center (LANSCE) and provided improvement in the measurement of the neutron spectrum in the energy regions above 20 MeV when compared to the standard BSS (Burgett, 2008 and Howell et al., 2009).

However, when the initial test of the system was carried-out at LANSCE, the BSE had not yet been calibrated. Therefore the objective of the present study was to perform calibration measurements. These measurements were carried out using monoenergetic neutron reference beams at the Physikalisch-Technische Bundesanstalt (PTB), Braunschweig, Germany.

2. Materials and Methods

2.1. Bonner Sphere Extension – System description

The BSE design is briefly described here, and a more thorough description is provided by Burgett (2008) and by Howell et al (2009). The BSE consists of two basic modules which we designate the small assembly and the large assembly use the 7.62 cm (3-in) and 12.70 cm (5-in) Bonner spheres, respectively. In the small assembly a 7.62 cm Bonner sphere is surrounded by an Al shell (7.62 cm inner diameter [ID] and 12.7 cm outer diameter [OD]) filled with Cu, Pb, or W. The small assembly can be further encased in a polyethylene shell with a 20.32 cm OD. The large assembly has a similar design but uses a 12.7 cm (5-in) Bonner sphere surrounded by a larger Al shell (12.70 cm ID and 17.78 cm OD) filled with Cu, Pb, or W. Similar to the small assembly, the large assembly can be further encased in a polyethylene shell with a 30.48 cm OD. The system can accommodate either the Ludlum $^6\text{Li(Eu)}$ scintillator or activation foils placed on a polyethylene holder (with similar dimensions to the Ludlum scintillator).

The extended sphere nomenclature is defined as follows X-Y bare or X-Y covered where X designates the size of the core Bonner sphere (either 3-in or 5-in), and Y designates the fill material (Cu, W, or Pb), and bare or covered indicates if the assembly is encased in an outer polyethylene shell. There are a total of 12 extended sphere combinations in the BSE measurement system, listed in Table I. A photograph of the small assembly with Pb shell and outer polyethylene sphere is shown in Fig. 1. In this photo, the top portions of the Pb and outer polyethylene shells were removed for the photograph.

2.2 Response Functions – MCNPX Calculations

Although response functions were calculated as part of an earlier work, (Burgett, 2008 and Howell et al., 2009) they were recalculated for this project with a larger number of particle histories (5×10^{10}) to reduce statistical uncertainties to less than 1.0% for all energy bins. Response functions were calculated using Monte Carlo N-Particle Code, eXtended

(MCNPX), version 2.7a (Hendricks et al., 2003) using 500 equally spaced logarithmic energy bins between 0.01 eV and 1 GeV for each sphere-detector ($^6\text{Li}(\text{Eu})$ scintillator) combination.

Responses were modeled for the standard Bonner spheres which have diameters of 5.08 cm (2-in), 7.62 cm (3-in), 12.70 cm (5-in), 20.32 cm (8-in), 25.40 cm (10-in), and 30.48 cm (12-in), as well as for the 12 extended spheres. The beam orientation was defined perpendicular to the detector (Y-direction) for these simulations. This orientation corresponds to the measurement orientation used for the calibration measurements. Neutron transport was carried out using three sources of data; ENDF-B.VI.8 (Frankle, 1996) cross section data was used for transport below 20 MeV, LA150 cross section data for transport above 20 MeV, and CEM03 physics models (Mashnik, 2006) for neutron transport above 150 MeV. The response functions for each of the sphere-detector combination was normalized to a unit neutron source i.e. n, α reactions for the $^6\text{Li}(\text{Eu})$ scintillator per unit neutron fluence rate. The calculated response functions are shown in Fig. 2.

2.3 Calibration Facility

Calibration measurements were carried-out in Division 6 (Department 6.4) at the PTB, Braunschweig, Germany. The PTB is the German National Metrology Institute and Division 6 “Ionizing Radiation” deals with radioactivity as well as photon and neutron metrology and dosimetry. One of the main tasks of Department 6.4 is the production of mono-energetic neutron reference fields according to the international standard ISO 8529-1 for the characterization and calibration of detectors and dosimeters (Nolte et al., 2004). The facility has a large open geometry experimental hall which minimizes backscattered neutrons. The following monoenergetic reference beams were used for these experiments: 14.8 MeV, 1.2 MeV, 565 keV, and 144 keV.

The PTB neutron reference fields are so-called quasi-monoenergetic neutron fields. The quasi-monoenergetic fields are produced by nuclear reactions induced by charged particle beams interacting in thin neutron-producing target layers. In addition neutrons produced in the target layer interact with the target backing and target mounting arrangements and are afterwards registered by a spectrometer (or by any device undergoing calibration). Although the contribution of these target-scattered neutrons is only 1.5 % to 2 % the spectra of the direct (neutrons generated by the neutron producing reaction) neutrons, taking into account the thickness of the target layer, as well as that of the target-scattered neutrons can be calculated using the Monte Carlo program TARGET developed at PTB (Schlegel and Guldbakke, 2001, and Schlegel, 2005). The direct and the target-scattered components of the spectra, as well as the total spectra (sum of direct and scattered components) are plotted in Fig. 3.

2.4. Calibration Measurements

Measurements were carried-out for the 4 beam energies using the full set of 12 extended spheres and 6 standard Bonner spheres (Table 1). The measurement location was 1.8 m from the target. Each measurement was repeated with and without a shadow cone (SC). When the shadow cone was in place, direct neutrons were blocked from the detector. Counts from the $^6\text{Li}(\text{Eu})$ scintillator were recorded for each experimental measurement. In addition, data from two PTB detectors were recorded: [a] beam charge (Q) measured using a Faraday cup and [b] counts from a neutron monitor of “long counter” design at 16° with respect to the ion beam and 6 meters from the target.

2.4. Data Analysis

2.4.1 Measured sphere response—The measured response for each detector sphere combination for each of the 4 beam energies was determined using equations 1 and 2. The LiI counts (N_{meas}) due to direct neutrons were determined according to equation 1:

$$N_{meas} = M_B - \left[\left(Q_B / Q_{SC} \right) * M_{SC} \right] \quad \text{Equation 1}$$

The measured sphere response, R_{meas} , was determined according to equation 2:

$$R_{meas} = \frac{N_{meas}}{(\Phi / Q) (FSA * Q_B)} \quad \text{Equation 2}$$

where,

Q_{SC} = Faraday cup charge reading with SC, (counts)

Q_B = Faraday cup charge reading bare i.e. without SC, (counts)

M_{SC} = measured LiI detector reading with SC, (counts)

M_B = measured LiI detector reading bare (counts)

FSA = beam specific factor ($\mu C/\text{counts}$)

Φ/Q = fluence per unit charge at 1.8 m from target ($\text{cm}^{-2} \mu C^{-1}$);

2.4.2 Energy weighted measured sphere response—Each sphere has a region of the neutron energy spectrum that it is best suited to detect. For example, responses for the large polyethylene spheres and extended spheres are best suited to detect the high energy component of a neutron spectrum and therefore possess a higher importance for 14.8 MeV compared to 144 keV. During the unfolding process, the impact of the large sphere's count rate for a 144 keV spectra is considerably lower than the small polyethylene spheres. This lower importance can be observed by omitting the larger sphere's results from the unfolding process for low energy neutron fields. Conversely, the small polyethylene spheres are best suited to detect the low energy component of the neutron spectrum, and therefore have a higher importance for 144 keV compared to 14.8 MeV. During the unfolding process, because the small sphere's response is highly important at low energies, it cannot be omitted for unfolding. Based on this information, we carried out additional analyses to weight the measured responses (R_{meas}) of each sphere based on its sensitivity to the different calibration beam energies to define energy weighted measured responses ($R_{meas-ew}$). Mathematically these calculations were carried-out using an ANCOVA analysis and the corresponding covariance matrix. Details are to be published in a future paper

2.4.3 Calculated sphere response—First, the PTB total fluence spectra (144 keV, 565 keV, 1.2 MeV, and 14.8 MeV) were rebinned to correspond to energy bins of BSE response functions. Then, the MCNPX calculated response function for each sphere was multiplied by each of the rebinned spectra. Finally, the expected response for each energy/sphere combination was taken as the sum of this product for each energy/sphere combination.

2.4.4 Comparison of measured and calculated sphere response - sphere specific correction factors—The percent difference between the measured and calculated responses was calculated for each sphere and energy.. Then the mean percent

difference for each sphere (averaged for the 4 beam energies) was calculated. These calculations were carried-out using both R_{meas} and the $R_{\text{meas-ew}}$.

3. Results and Discussion

The difference between measured (non-energy weighted) and calculated responses for individual spheres ranged between 9.7 % and 19.2 %, and the arithmetic mean (and standard deviation about the mean) for all spheres was $(15.2 \pm 1.1) \%$. The standard deviation of the arithmetic mean provides a measure of the spread of correction factors and is not an estimate of an uncertainty in the correction factors. Measured and calculated responses for each detector-sphere combination averaged over all beam energies are provided in Table 2. Differences between the measured and calculated responses can be attributed to several factors. First, the detector efficiency for (n, α) reactions was assumed to have 100 % efficiency in the MCNPX model. However, the true efficiency is several percent lower. This arises due to lack of knowledge of the precise amount of Li-6 as well as an imperfection in the $^6\text{LiI(Eu)}$ scintillator. This accounts for the median offset of all of the calculated responses. The variation about the median offset in the measured and calculated data can be attributed to differences in modeled and actual sphere diameters and material composition in individual spheres. Finally, differences between measured and calculated responses may also be due to small air gaps and slight variations in aluminum thicknesses between the detector and sphere surfaces. These air gaps and subtle machining differences are somewhat irregular and difficult to accurately model. The effect from air gaps is likely most significant for the smallest spheres i.e. 2-in and 3-in spheres.

The difference between energy-weighted-measured and calculated responses for individual spheres ranged between 7.9 % and 16.7 % and the arithmetic mean for all spheres was $(10.9 \pm 1.8) \%$. A plot of the difference between energy-weighted-measured and calculated response for each sphere is shown in Fig. 4. Since these results are correlated to the energy of response, the uncertainty in this analysis method is significantly lower. These energy-weighted response factors will be used as sphere specific correction factors because they account for the differences between measured and calculated responses as well as being weighted for variations in detector response to different energies and more correctly represent the true offset from the calculated responses.

4. Conclusions

The BSE was calibrated using ISO 8529 monoenergetic beams at PTB. Energy-weighted sphere specific correction factors were determined. These correction factors will be applied for all future measurements carried-out with the BSE.

5. Future Directions

Future research will include similar experiments for additional monoenergetic beams available at PTB, specifically for 24 keV, 5 MeV and 19 MeV. These data will then be incorporated into the sphere specific correction factors. Future work will focus on using the BSE to measure work place neutron spectra. We hope to focus on measurements of secondary neutron spectra at high energy proton therapy facilities.

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Fig. 1. Photograph of the small assembly with Pb shell and outer polyethylene sphere. The top portions of the Pb and outer polyethylene shells were removed for the photograph.

Fig. 2.
Response functions for the standard Bonner spheres and extended spheres in the BSE.

Fig. 3. Plot of the direct and the scattered components of the PTB spectra used for this calibration, as well as the total spectra (sum of direct and scattered components).

Fig. 4. Plot of the energy weighted percent difference between measured and calculated response for each sphere. Mean difference ratio for all spheres was 10.9 % and is shown as solid dark grey line. The dashed grey lines above and below the mean are ± 1 standard deviation.

Table 1

List of standard Bonner spheres and extended spheres in the small and large assemblies of the Bonner sphere extension. The standard Bonner spheres are listed in terms of sphere diameter in cm (common nomenclature are provided in parenthesis). The sphere nomenclature for the extended spheres is defined as follows: X-Y bare or X-Y covered, where X designates the size of the core Bonner sphere (either 3'' or 5''), and Y designated the fill material (Cu, W, or Pb), and bare or covered indicates if the assembly is encased in an outer polyethylene shell.

Standard Bonner Spheres (cm)	BSE Spheres Small Assembly	BSE Spheres Large Assembly
5.08 (2-in)	3-Cu bare	5-Cu bare
7.62 (3-in)	3-Pb bare	5-Pb bare
12.7 (5-in)	3-W bare	5-W bare
20.32 (8-in)	3-Cu covered	5-Cu covered
25.4 (10-in)	3-Pb covered	5-Pb covered
30.48 (12-in)	3-W covered	5-W covered

Table 2

Difference between measured (non-energy weighted) and calculated responses for each detector-sphere combination averaged over all beam energies. Note that for the 5-W covered sphere measurements were only completed for 2 beam energies (1.2 MeV and 565 keV).

Sphere	mean	std dev
2-in	19.2%	16.8%
3-in	13.6%	11.3%
5-in	18.0%	11.6%
8-in	15.4%	7.1%
10-in	17.4%	3.5%
12-in	14.8%	4.0%
3-Cu bare	17.3%	6.7%
3-Pb bare	17.9%	6.1%
3-W bare	16.7%	3.4%
3-Cu covered	12.1%	5.0%
3-Pb covered	15.1%	6.9%
3-W covered	10.4%	8.9%
5-Cu bare	15.5%	1.0%
5-Pb bare	14.5%	2.4%
5-W bare	13.8%	4.9%
5-Cu covered	9.7%	6.6%
5-Pb covered	16.7%	6.1%
5-W covered *	17.0%	22.7%
Mean	15.3%	7.5%

* only 2 measured data points