Unfolding the fast neutron energy distribution of a NE230 deuterated liquid scintillator detector using the MAXED code

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Abstract. A NE230 deuterated liquid scintillator detector has been used to measure the neutron fluence energy distribution in air of a neutron beam of energy up to ~ 48 MeV. The fluence energy distribution was obtained from measurement of the pulse height distribution by the NE230 detector using the Bayesian unfolding code MAXED with a response matrix that was determined experimentally. The unfolded fluence energy distribution obtained is compared with the fluence energy distribution of the beam measured with a NE213 natural hydrogen liquid scintillator detector using the time-of-flight method.

1. Introduction

Detailed knowledge of the neutron fluence energy distributions are useful in basic research and applications, particularly in applications such as neutron radiotherapy for the treatment of cancer [1]; radiobiology, studying the biological effectiveness of neutrons [2] and radiation protection at nuclear facilities [3]. In neutron radiotherapy, this knowledge is important to calculate the energy distributions of secondary charged particles, and to characterize the radiation quality and absorbed dose both inside and near to the area under treatment. Measuring these neutron fluence energy distributions pose a challenge at energies above 20 MeV since reaction cross-sections above 20 MeV have either not been measured or are not correctly calculated by present nuclear models.. In principle, these fluence energy distributions can either be calculated by Monte Carlo Methods or measured experimentally [4].

There are a variety of methods that can be used to measure neutron beam fluence energy distributions [5]. Of these methods the time-of-flight is the most widely, especially if pulsed beam is available. However, for measurements in water (simulating human tissue) the neutron flight path is undefined, alternative methods need then to be used, such as those based on unfolding analyses [1]. In unfolding analyses the fluence energy distribution has to be unfolded from the corresponding pulse height pulse height distribution that is recorded from the detector which results from the neutron interactions in the detector medium. The fluence energy distribution $\Phi(E)$, the pulse height distribution $\frac{dN}{dH}$, and the detector response $R(H,E)$, are related through the Fredholm integral equation of the first type as below [6] such that;

$$\frac{dN}{dH} = \int R(H,E)\phi(E)dE \tag{1}$$

When pulse height distribution is recorded by a multichannel analyzer, Equation. (1) takes the discrete form;

$$N_i = \sum_j R_{ij}\phi_j \tag{2}$$

where N_i $(i=1, 2, ..., n)$ is the recorded counts in the ith channel, Φ_j $(j=1, 2, ..., m)$ is the radiation fluence in the jth energy interval, and R_{ij} is the response matrix coupling the ith pulse height interval with the jth energy interval. Equation (2) can be transformed into the matrix notation such that;

$$N = R\phi \tag{3}$$

Where $\mathbf{N}=(N1, N2, ..., Nn)^T$, $\boldsymbol{\Phi}=(\Phi1, \Phi2, ..., \Phi m)^T$, $\mathbf{R}$ is the response matrix with size of $n\times m$. To obtain the neutron fluence energy distribution from the measured pulse height distribution equation (3) need to be inverted. Several mathematical methods and computing algorithms have been used to solve equation (3), such as least-squares [7], Monte Carlo Methods [8], genetic algorithm [9], and populated artificial neural networks in recently years [10]. Using any one of the mathematical methods to obtain the fluence energy distribution from the measured pulse height distribution requires reliable knowledge of the detector response matrix. Monte Carlo codes (eg. MCNPX) which may be used to simulate the detector response matrix, are limited to neutron energies below 20 MeV, since the non-elastic contribution to the reaction cross-sections is significant and have either not been measured or are not correctly calculated by present nuclear models.

This paper presents the overall procedure of measuring and unfolding the fast neutron fluence energy distribution of a neutron beam of energy up to ~ 48 MeV, in air, with NE230 deuterated liquid scintillator detector, using an experimentally determined response matrix. The unfolded fluence energy distribution obtained is compared with the fluence energy distribution of the beam measured with a NE213 natural hydrogen liquid scintillator detector using the time-of-flight method [11].

2. Experimental procedures and Data analysis

Experiments were conducted at the neutron time of flight facility at the iThemba LABS in Faure, outside Cape Town, South Africa. Fig. 1 is a schematic diagram showing the details of the beam line in the neutron vault, the shielding in the experimental area and the positions of the detectors including the neutron monitor.

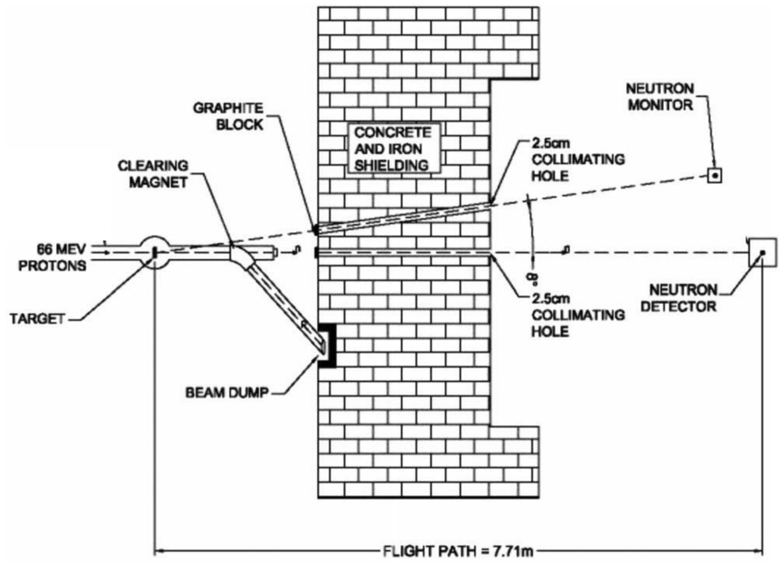

Figure 1. Schematic diagram of the neutron beam line, shielding and detector.

Neutrons were produced by bombarding either a Li metal target (thickness 1 mm) or a Be metal target (thickness 10 mm) or a graphite target (thickness 10 mm) with a pulsed beam of 66 MeV protons from the iThemba LABS time-of-flight facility. A 2 m thick shielding wall (concrete and iron) separated the experimental area from the target. A circular aperture (25 mm diameter) in the wall provided a collimated neutron beam at angle 0° to the proton beam direction. The neutron beam profile measured at the end of the neutron flight path of 7.7 m was found to be uniform within 5% over a circular area of diameter 50 mm. Measurements of the neutron beams were taken with either the NE230 detector (25 mm diameter x 25 mm) or a reference detector NE213 detector (50 mm diameter x 50 mm) at a distance of 7.7 m away from the target. Both the detectors were equipped with LINK pulse shape discriminator units to suppress gamma rays and to select only events such as n-p elastic scattering or n-d elastic scattering and all heavier particles resulting from neutron interaction in the detector mediums [1 and 12].

All runs were normalised to the same number of neutrons measured by the neutron monitor. After applying the event selection procedures, data were analysed as follows. For the generation of the experimental response matrix, two-parameter distributions of events as a function of pulse height *L* and neutron time-of-flight *T* were obtained from the combined two parameter (*LT*) data obtained using the Li, Be and C targets. The neutron energy, *E* was determined from *T*. The pulse height response functions of the NE230 detector were determined at 29 equally spaced 2 MeV neutron energies ranging from 10 MeV to 66 MeV from the (*LT*) data. The response functions were then combined to form a response matrix of dimensions 29 (E) X 104 (L) as described in Brooks *et al.*[13]. The NE230 detector detection efficiency $\varepsilon_d(E)$ for each of the 29 energies were determined from the ratio of counts recorded (in the same neutron beam) by the NE230 detector and NE213 reference detector, respectively. The efficiency $\varepsilon_d(E)$ is given by the product of this ratio and the known detection efficiency $\varepsilon_p(E)$ of the NE213 detector, which was determined by reference to the n-p elastic scattering cross-section, as described in Klein and Brooks [5].

Applying pulse selection in the off-line analyses the pulse height distribution for deuterons and heavier charge particles resulting from the interactions of neutron beam of energy up to ~ 48 MeV (neutrons produced by a 66 MeV proton beam on a graphite target) with the NE230 detector medium was determined. The Bayesian unfolding code MAXED [14] using the experimentally determined response matrix was use to determine the neutron fluence energy distribution from the pulse height distribution. The MAXED code use an unfolding algorithm based on maximum entropy principle to problems of data analysis and require prior information in the form of a prior energy distribution to obtained solution energy distribution to equation (3). The code is available from the PTB Braunchweig, Germany. The unfolded fluence energy distribution obtained is compared with the fluence energy distribution of the beam measured with a NE213 natural hydrogen liquid scintillator detector using the time-of-flight method.

3. Results and discussion

In this work the pulse height distribution was unfolded with the MAXED code, using the experimentally determined response matrix with either the time-of-flight prior energy distribution containing a lot of information about the solution energy distribution or the flat prior energy distribution which contain no information about the solution energy distribution, as shown in figure 2. Figure 3 shows the results of the pulse height distribution measured (blue curve), together with refolded MAXED fit (red curve) from the unfolding using the time-of-flight prior energy distribution. The refolded MAXED fit agrees well with the measured pulse height distribution. A similar result was obtained from the unfolding using the flat prior energy distribution. Figure 4 shows results of the neutron fluence energy distributions obtained from the MAXED unfolding, using (a) the time-of-flight prior energy distribution (black solid circles) and (b) flat prior energy distribution (blue solid circles). In each frame the unfolded neutron fluence energy distribution obtained is compared with the fluence energy distribution (black solid line histogram) obtained by the time-of-flight method.

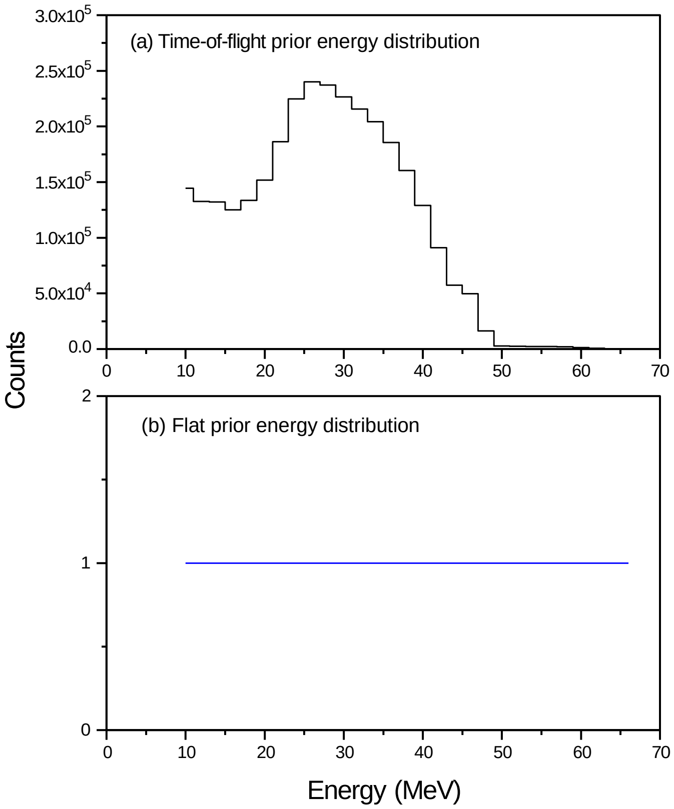

Figure 2. (a) Time-of-flight prior distribution and (b) flat prior distribution used in unfolding

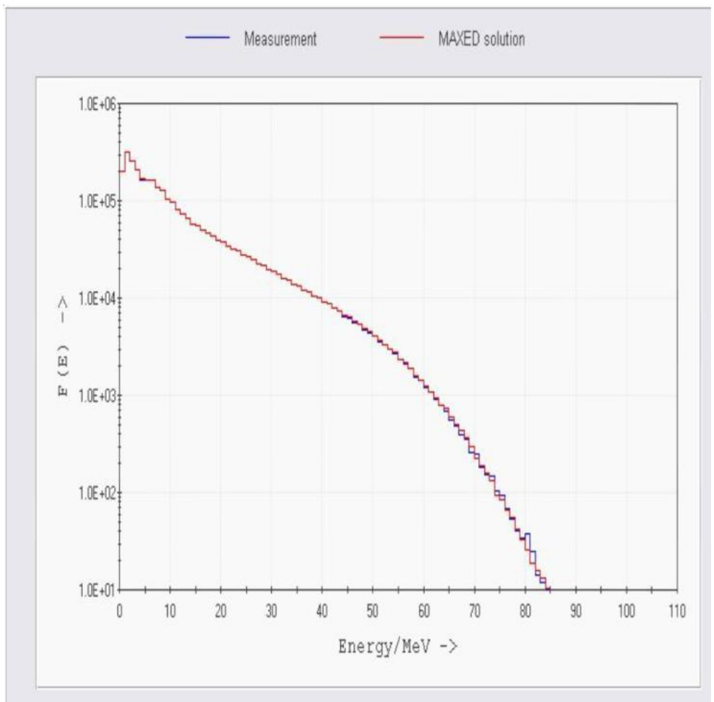

Figure 3. Measured pulse height distribution together with the refolded MAXED fit using the time-of-flight prior energy distribution.

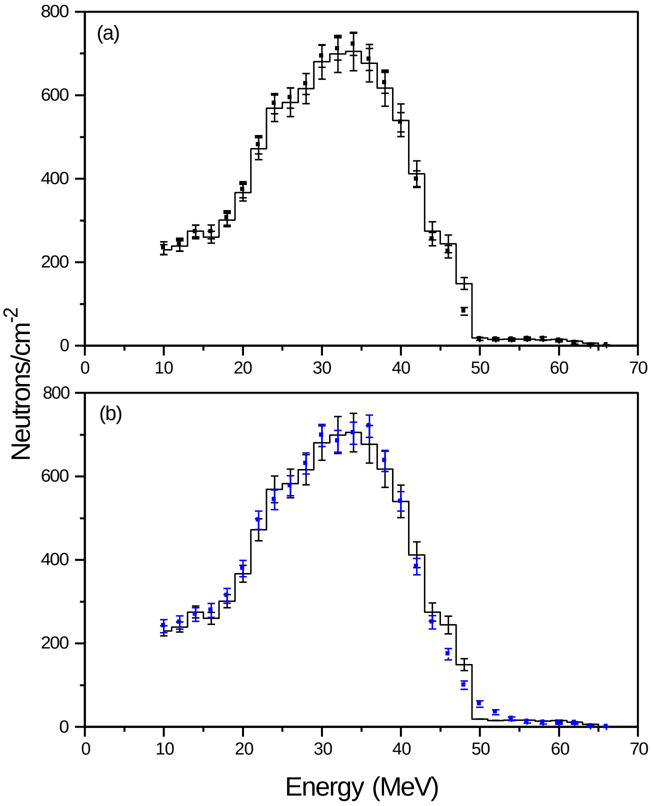

Figure 4. (a) Comparisons of fluence energy distributions (solid black circles) obtained with unfolding using time-of-flight prior energy distribution and fluence energy distributions (solid blue circles) obtained from unfolding using flat prior energy distribution with fluence energy distribution (solid line histogram) obtained with the time-of-fight method

Both fluence energy distributions obtained by unfolding agrees well with the fluence energy distribution obtained with the time of flight method. However, it can be seen from the plots that at high energies the unfolded fluence energy distribution obtained by unfolding using the time-of-flight prior energy distribution agrees better with the fluence energy distribution using the time-of-flight method. This better agreement obtained at higher energies with the time-of-flight prior energy distribution might be attribute to the fact that the prior information compensate for the response matrix which are less sensitive at higher energies due to the wall effect [1].

4. Conclusions

The work done demonstrates that the unfolding code MAXED with an experimentally determined response matrix can reliably determine the fast neutron fluence energy distribution of a neutron beam of energy up to ~ 48 MeV, in air. In future this work will be extended to increase the sensitivity of the response matrix at higher energy. Also the unfolding procedures will be use to investigate how well the unfolding can be use to determine the fast fluence energy distributions of quasi-mono- energetic beams at neutron energies above 20 MeV.

5. References

[1] Herbert M S, Brooks F D, Allie M S, Buffler A, Nchodu M R , Makupula S A, Jones D T L, Langen K M 2007 *Radiat. Prot. Dosim* Vol. **126**, No. 1–4, pp. 346–349

[2] Nolte R, Mhlbradt K, Meulders J, Stephan G, Haney M and Schmid E. *Radiation and environmental biophysics*, **44** (3), 201−209.

[3] Taniguchi S, Nakamura T, Nunomiya T, Iwase H, Yonai S, Sasaki S, Rokni S, Liu, J, Kase K and Roesler S 2003 *Nuc.Instru. and Meth* **A503**, 595

[4] Bohm T, Deluca P, Cox L, Maughan R, Jones D and Lennox A 1999 *Med. Phys.* **26,** 783−792.

[5] Brooks F and Klein H 2002 *Nucl. Instr. Meth.* **A476**, 1−1.
[6] Knoll G F 2010 *Radiation Detection and Measurement* fourth edition. Hoboken New Jersey: John Wiley & Sons, Inc.
[7] Koohi-Fayegh, Green S, Scott M C 2001 *Nucl. Instrum. Meth.* A **460:** 391−440
[8] Sanna R, Obrien K 1971 *Nucl. Instr. Meth.* **91**: 573−576
[9] Mukherjee B. BONDI-97 1999 *Nucl. Instr. Meth. A* **432**: 305-312
[10] Avdic S, Pozzi S A, Protopopescu V 2006 *Nucl. Instr. Meth. A* **565:** 742−752
[11] Herbert, M 2014 *Rad Prot Dosim* pp. 1-6.
[12] Adams J and White G 1978. *Nucl. Instr. and Meth* **156** 459−476
[13] Brooks F D, Buffler A, Allie M S, Herbert M S, Nchodu M R, Jones D T L, Smit F D, Nolte R, Dangendorf V 2007 *Rad Prot Dosim* Vol. **126**, No. 1–4, pp. 218–222
[14] Reginatto M, Goldhagen P. and von Neumann S 2002 *Nucl. Instr. Meth. A* **476** 342