Measuring response functions for a new compact neutron spectrometer

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Abstract. A compact neutron spectrometer consisting of a (0.6 x 0.6 x 12.0 cm^3) EJ-276 plastic scintillator coupled to a silicon photomultiplier has been designed. An essential aspect of the characterisation of the spectrometer is the measurement of detector response functions for neutron energies above 20 MeV. The process of producing response functions for neutron energies between 10 MeV and 60 MeV for the compact detector using neutron time-of-flight measurements at iThemba LABS is presented.

1. Introduction

The high energy neutron fields found in medical, aviation [1,2] and space environments [3,4] have serious impacts on both biological and technological systems. These fields are not well studied and understood, in part, due to a lack of suitable instrumentation. A new compact spectrometer has been developed at the University of Cape Town (UCT) with the main focus on the detection of neutrons produced by cosmic rays at aviation altitudes and in space. The device is comprised of an EJ-276 plastic scintillator coupled to a silicon photomultiplier (SiPM) and has been characterised with neutrons of energy up to 63 MeV at iThemba LABS.

To measure neutron energy spectra with scintillators outside a laboratory environment the method of spectral unfolding must be used, which requires accurate and detector-specific response functions. For neutron energies < 20 MeV response functions can be reliably simulated, however above 20 MeV the response functions must be measured due to poor knowledge of the cross sections for the many possible reaction channels. In this work the process of measuring response functions for the compact detector using ns-pulsed neutron beams at iThemba LABS is presented.

2. Methodology

2.1. Measurements

The spectrometer consists of an EJ-276 plastic scintillator (0.6 x 0.6 x 12.0 cm^3) capable of pulse shape discrimination coupled to a 0.6 x 0.6 cm^2 SensL C-series MicroFC-60035 silicon photomultiplier operated at +28.5 V using an external power supply. The measurements with the compact spectrometer are referenced to a 5⌀ x 10 cm^3 BC-501A liquid scintillator coupled

to a 12-stage photomultiplier tube (PMT). The data for both detectors were acquired digitally using a CAEN DT5730 digitiser and custom acquisition software [5,6].
The data presented in this paper were acquired during a measurement campaign at the iThemba LABS D-line fast neutron facility [7,8]. Neutron beams were produced via ^{7}Li(p, xn) reactions using proton beams available from the $k = 200$ separated sector cyclotron. During this campaign a 66 MeV proton beam was used, producing neutrons with a maximum energy of 63 MeV.

2.2. *Time-of-flight*

Time-of-flight (ToF) [9] is a commonly used technique for determining the energy spectrum of a neutron beam. A time-of-flight parameter may be defined from the time between the event pulse in the detector and reference pulse associated with the ns-pulsed proton beam. Figure 1 shows the ToF spectra measured at 16° relative to the proton beam for the two detectors. The peaks centred at 26.7 ns correspond to the gamma rays produced at the target and the distribution of events above ∼ 80 ns are associated with neutrons. The gamma ray events are used as a calibration point for the ToF using the known distance (8.00 m) between the target and the front of the detector.

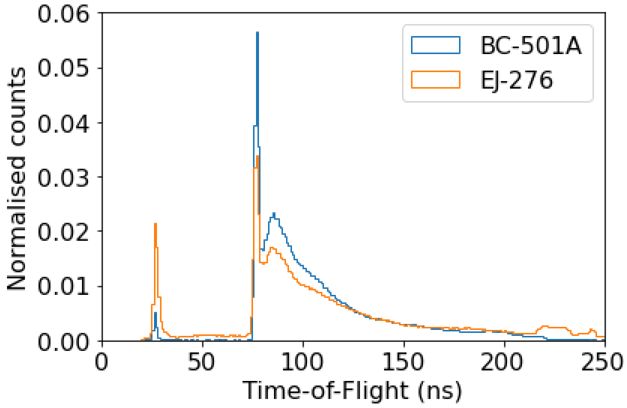

Figure 1: Time-of-flight spectra for a 66 MeV proton beam incident on a 8.0 mm Li target for the compact EJ-276 and reference BC-501A detectors.

2.3. *Pulse shape discrimination*

The EJ-276 plastic scintillator used in this project produce pulses with different rise time characteristics for events produced by electron excitation (gamma ray interactions) and events produced by recoil hadrons (neutron interactions). This property is utilised to separate the two event types in a technique known as pulse shape discrimination (PSD). There are several methods for performing digital PSD. In the data presented the charge comparison method was used:

$$S = k\frac{Q_s}{Q_L} + c, \tag{1}$$

where S is the pulse shape parameter, Q_s is the integral of the pulse over a short time period (typically 10 ns for the BC-501A detector and 42 ns for the EJ-276 detector), Q_L is the integral of the pulse over a long time period (800 ns for the BC-501A detector and 1400 ns for the EJ-276 detector) and k and c are scaling constants [10]. The long integral is also used as a measure of the size of the pulse, which is related to the light output and energy of the event. Measurements of gamma rays with known energy are used to to calibrate the scaling between long integral and light output (L, units MeV$_{ee}$) which is assumed to be linear. Figures 2 (a) and (b) show density plots for pulse shape parameter S as a function of light output parameter L for both detectors and illustrate the cuts used to separate the gamma ray events from the neutron events.

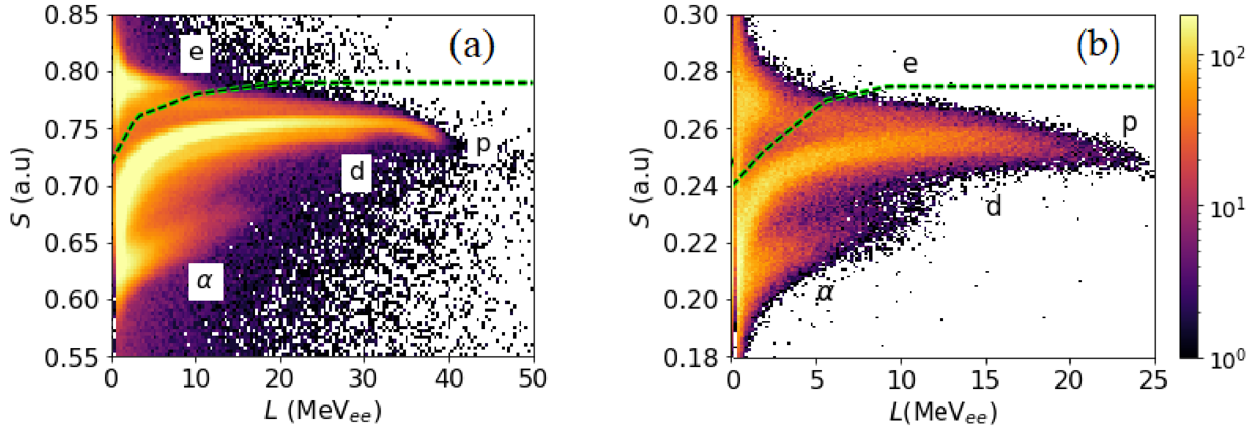

Figure 2: Counts as a function of light output parameter (L) and pulse shape parameter (S) for events in the (a) BC-501A and (b) EJ-276 detectors when exposed to neutrons and gamma rays produced by the irradiation of a 8.0 mm Li target by a proton beam of energy 66 MeV. Loci associated with recoiling electrons (e), protons (p), deuterons (d), tritons (t) and alpha-particles (α) are indicated. The dotted lines indicates the cuts used to separate neutron and gamma ray events.

2.4. Calculation of neutron energy spectrum

After the neutrons have been separated from the gamma ray events using PSD, the neutron ToF spectrum can be transformed to an energy spectrum by calculating the relativistic kinetic energy of the neutrons [11]. A comparison of the energy spectra obtained from the ToF measurements for the two detectors after correcting for efficiency is shown Figure 3.

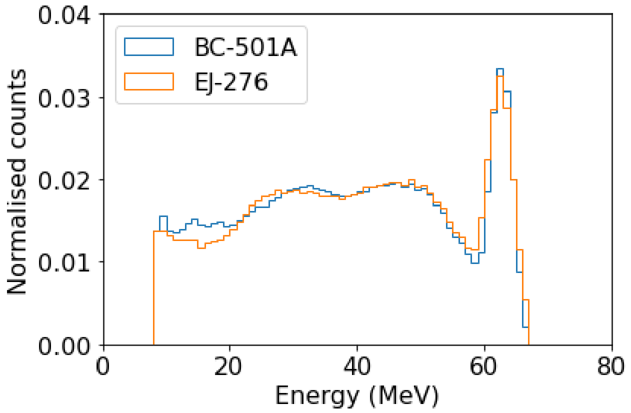

Figure 3: Neutron energy spectra from ToF for the compact EJ-276 and reference BC-501A detectors measured at 16° for a 66 MeV proton beam incident on a 8.0 mm Li target.

2.5. Response functions

Spectrum unfolding uses a deconvolution algorithm and a matrix of energy dependent detector response functions to calculate an energy spectrum from a measured light output spectrum [12]. In the present work, the measured response functions are made by taking cuts in the neutron energy spectrum obtained through ToF (Fig. 3) and producing a light output spectrum from the events within the cut. If the energy window is sufficiently small (in this work 0.5 MeV) then the light output spectrum may be regarded as being for nearly monoenergetic neutrons. By repeating this over the full energy range of the available energy spectrum a response matrix is formed.

Figure 4 shows a selection of the response functions for the the compact EJ-276 detector and the BC-501A reference detector. The detectors have similar response functions at lower energies ($<$ 10 MeV), however as the energy increases the response functions for the EJ-276 detector begin to deviate significantly from those of the BC-501A reference detector. The difference in detector response is attributed largely to differences in light collection characteristics for the two detectors and highlights the necessity of having detector specific response functions.

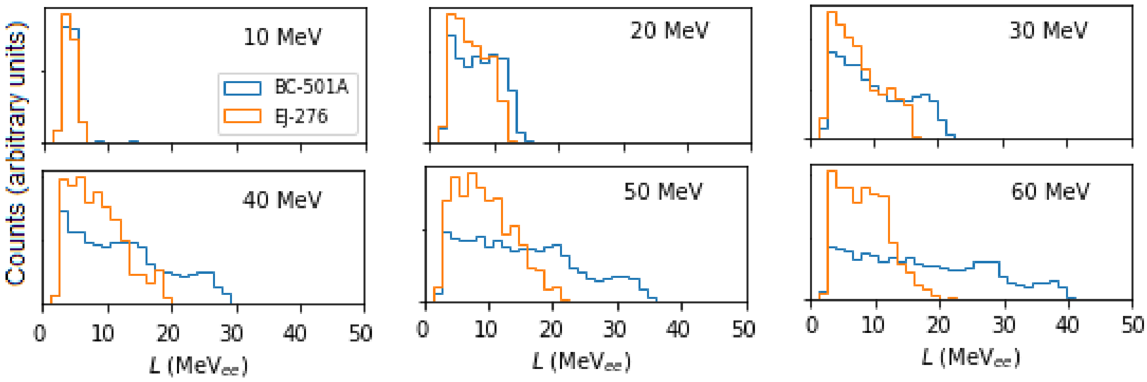

Figure 4: Response functions measured for the BC-501A and EJ-276 detectors at average energies of 10 MeV, 20 MeV, 30 MeV, 40 MeV, 50 MeV and 60 MeV.

3. Conclusion

A compact neutron spectrometer consisting of a (0.6 x 0.6 x 12.0 cm^3) EJ-276 plastic scintillator coupled to a silicon photomultiplier has been constructed and is in the process of being characterised for neutrons up to 100 MeV. Response functions were measured at iThemba LABS using a ns-pulsed 66 MeV proton beam and neutron time-of-flight spectroscopy. The response functions will be used to build a response matrix so that neutron spectroscopy can be performed outside of a laboratory environment through spectrum unfolding. Further characterisation of the spectrometer and validation of the response functions is in progress with data acquired at the UCT n-lab and IRSN AMANDE fast neutron facility.

Acknowledgements

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References

[1] Goldhagen P, Clem J and Wilson J 2004 *Rad. Prot. Dosim.* **110** 387-92
[2] Clem J et al. 2004 *Rad. Prot. Dosim.* **110** 423-8
[3] Grieder P 2001 *Cosmic Rays at Earth: Researcher's reference manual and data book* (Elsevier)
[4] Bagshaw M and Illig P 2019 *Travel Medicine (Fourth edition)* (Elsevier) pp 429-36
[5] Sole C 2022 *A new digital data acquisition system for neutron metrology* MSc thesis (University of Cape Town)
[6] Comrie A 2016 *A new compact neutron spectrometer* PhD thesis (University of Cape Town)
[7] Mosconi M, Musonza E, Buffler A, Nolte R, Röttger S and Smit F 2010 *Radiation Measurement* **45** 1342-5
[8] Ndlovu N, Boso N, Buffler A, Geduld D, Hutton T, Lacoste V, Leadbeater T, Malekam P and Smit F 2020 *In 22nd Int. Conf. on Cyclotrons and their Applications* 181–4
[9] Copley J and Udovic J 1993 *Journal of research of the National Institute of Standards and Technology* **98** 71
[10] Comrie A, Buffler A, Smit F, and Wörtche H 2015 *Nucl. Inst. Meth.* A **772** 43–9
[11] Herbert M et al. 2014 *Rad. Prot. Dosim.* **161** 377–82
[12] Reginatto M, Goldhagen P and Neumann S 2002 *Nucl. Instr. Meth.* A **476** 242–6