

Light in plastic, it's fantastic:
A new fast neutron spectrometer with
EJ-276 plastic scintillator and silicon
photomultipliers in a novel geometry

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Master of Science



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Abstract

Fast neutron fields are present in aviation, space, radiotherapy, and nuclear research environments. Characterisation and continuous monitoring are required for risk assessment and workplace dosimetry as neutrons present particular radiation protection challenges. These neutron fields are often coupled with gamma ray fields, cover a large range in energy and intensity, and have variable directional characteristics. Existing techniques rely on systems that are often bulky, unsafe to use outside of laboratory environments, or require complicated operation. A compact detector system has been developed at the University of Cape Town for fast neutron spectrometry and dosimetry based on plastic scintillator, silicon photomultipliers, and digital data acquisition.

This work presents the characterisation and calibration of a detector system suitable for neutron measurements up to 20 MeV composed of an EJ-276 scintillator machined to a novel spherical geometry, a MicroFC-60035 silicon photomultiplier, and a DT5730 digitiser. Measurements of well-characterised fast neutron fields were made at the n-lab, University of Cape Town, and international fast neutron metrology facilities AMANDE (IRSN, France) and PIAF (PTB, Germany). Detector response functions were measured between 1.0 MeV and 16.0 MeV using time-of-flight analyses, and simulations of the detector system with Geant4 were used to determine the neutron detection efficiency. Neutron energy spectra of monoenergetic and broad energy neutron fields were unfolded using the efficiency-corrected detector response functions, demonstrating the capabilities of the device as a neutron spectrometer.

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Chapter 1

Introduction

Neutrons are produced as secondary radiation from interactions of charged particles with matter in a number of environments [1–3] and pose a risk to both biological and electronic systems [4, 5]. Historically, measurements of fields of this type were conducted using liquid organic scintillators, made of dangerous materials and requiring high voltage photomultipliers, or Bonner sphere systems, which are bulky and are complicated to operate. The development of plastic scintillators which allow for neutron-gamma ray event discrimination, silicon photomultipliers, and digital data acquisition systems has made the creation of compact and safe-to-use neutron spectrometers possible.

Neutron fields measured in high-energy particle accelerator facilities [1], in proton therapy centres [2], and at aviation altitudes due to cosmic rays incident on the atmosphere [3] all feature similar shapes (Figures 1.1 and 1.2), with peaks around 1 MeV and 100 MeV. In many of the environments of interest the neutron fields can be isotropic, or at least not biased strongly in a particular direction, since they are produced by charged particles incident on shielding and structural materials. An effective workplace neutron spectrometer suitable for such environments should thus be insensitive to the direction of incident radiation.

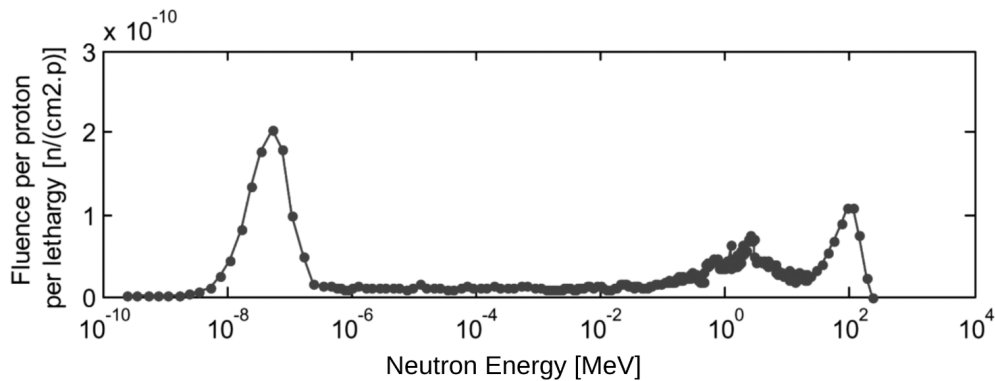


Figure 1.1: Neutron energy spectrum measured in a proton therapy centre by a Bonner sphere system, for 226.7 MeV protons incident on a water phantom [2].

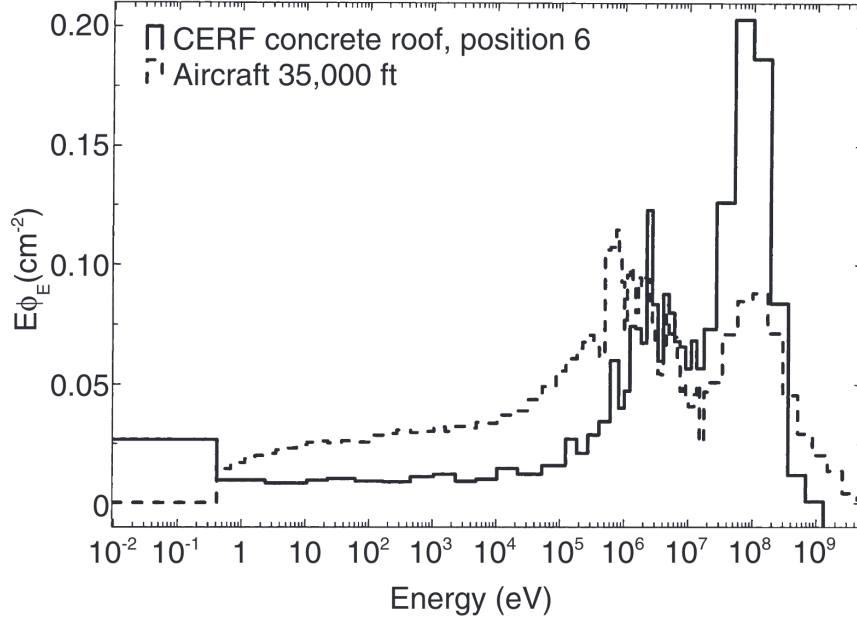


Figure 1.2: Comparison of neutron energy spectra between a measurement made outside of the concrete shielding at the CERN–EU high-energy Reference Field (CERF) facility [1] and a calculated spectrum for an altitude of 10.6 km [6].

Produced along with neutrons in these environments are gamma rays as the production of neutrons often results either in an excited nucleus, which decays by emission of one or more gamma rays, or neutron interactions with the environment, which result in prompt gamma ray emission [7]. For this reason, any detector used to measure these fields must either be insensitive to gamma rays, or be able to distinguish between neutron- and gamma ray-induced events.

Neutrons incident on biological systems can result in damage to DNA by single and double strand breaks [8], which can lead to higher cancer risks. Neutrons incident on electronic systems can lead to high rates of electronic failures [9] due to the impact of recoil charged particles interacting with transistors, electronics, and magnetic fields. If shielding is not present, or is impractical to implement, measurement and monitoring of neutron workplace fields is vital to determine the received dose and thus the risk of cancer in humans or failures in electronic systems.

The use of simulation to determine the absorbed dose in workplace environments is common and works well in many applications [10–12]. Where it falls short is in environments where the neutron field is either not well understood, or is subject to rapid change as a result of external processes, such as energetic solar events increasing solar cosmic ray flux on hour timescales. For this reason, compact neutron spectrometers are required to easily and quickly measure workplace fields in order to improve simulation models, or to be constant monitors in environments where the field is still impractical to simulate.

Neutron spectroscopy is a well established field, with a number of techniques covering a wide range of applications. In laboratory applications, the time-of-flight technique is well understood and trusted, but it requires a nanosecond-pulsed particle accelerator. Thus, unfolding techniques are often used, where the neutron energy spectrum is determined by a process of reconstructing the measured response from an array of known responses to monoenergetic neutrons. Bonner sphere systems are a common example of this, where a spherical gas-filled proportional counter is used along with a range of moderating shells and the measured responses combined and then unfolded. This technique can produce neutron energy spectra with good energy resolution, such as in Figure 1.1, but the measurement procedure is time consuming and the detector system is often bulky, thus its application as a workplace monitor, particularly a compact one, is limited.

Passive detection techniques are often used, such as placing materials that will be activated by incident neutrons (gold, copper, etc.) in the workplace environment and measuring the resulting gamma ray emission spectrum to infer the neutron fluence spectrum from which materials were activated and to what degree. This technique is extremely useful in applications where the workplace has been exposed to a large dose of radiation and that dose needs to be determined, but as a constant monitor it is not adequate as it would require the sample to be analysed regularly.

Detectors based on organic scintillators are an attractive option for this application as they are typically sensitive over large ranges of incident particle energies (dependent mostly on their size and shape) and are capable of neutron-gamma ray discrimination. Liquid organic scintillators (the industry standard for energy resolution and pulse shape discrimination quality) however, generally use flammable and toxic xylene-based materials and are kept in fragile glass containers for storage and operation. Because of this, as well as their common pairing with fragile and high voltage photomultiplier tubes, their application outside of laboratory environments is extremely limited.

Three new technologies have allowed for the development of detector systems that are capable of measurements of neutrons in the energy ranges of interest, while remaining robust to use in out-of-laboratory environments: pulse shape discrimination-capable plastic scintillators; compact and low-voltage silicon photomultipliers; and compact digitisers for digital data acquisition.

1.1 Previous work

The Department of Physics at the University of Cape Town has been conducting research for a number of years with the aim of developing a compact neutron spectrometer capable of measuring neutrons up to an energy of 120 MeV. The work has included the development and characterisation of a digital data acquisition system [13–15], and the development of a number of silicon photomultiplier-based compact neutron spectrometers [13, 16].

Work began with the development of prisms of plastic scintillator coupled to silicon photomultipliers in order to evaluate the energy resolution and pulse shape discrimination ability of EJ-276 organic plastic scintillator, made by Eljen Technologies [17]. Response

functions were produced through Monte Carlo radiation transport simulations using Geant4 and measurements at neutron metrology facilities such as iThemba LABS in South Africa [18] and IRSN AMANDE in France [19].

These previous detector systems were designed with the intention of measuring neutrons with energies up to 120 MeV to test the ability of a detector system made of these new components, but were extremely sensitive to the direction of incident radiation. This is a useful property in environments where the direction of incident neutrons is well known, such as nuclear reactors, but for general purpose workplace monitoring a more isotropic response is needed.

1.2 Objectives of the current work

This work aims to advance the development of a compact fast neutron spectrometer for the characterisation and monitoring of workplace fields, using plastic scintillators and silicon photomultipliers with digital data acquisition techniques. The neutron fields of interest tend to be diffuse, so a spectrometer used for measuring these fields should be relatively insensitive to the direction of incident radiation. A novel spherical scintillator shape, made possible by the use of EJ-276 plastic scintillator, was investigated in the interest of direction insensitivity.

The detector was designed to be capable of neutron spectrometry up to 20 MeV and thus a $\varnothing$ 25 mm sphere of EJ-276 was chosen. The main objectives of the work were to:

- optimise the design of a compact spectrometer capable of detecting neutrons with energies up to 20 MeV using a spherical plastic scintillator and silicon photomultipliers;
- investigate the response of the detector to the direction of incident radiation;
- characterise the detector response as a function of neutron energy, up to 20 MeV in monoenergetic and broad spectrum neutrons fields;
- simulate the energy-dependent neutron detection efficiency of the detector system; and
- measure neutron energy spectra through unfolding methods.

Chapter 2

Neutron spectroscopy techniques

Scintillation detectors, which were first used for particle detection in the early 20th century [20] and for neutron spectroscopy in the 1950s [21], work by taking advantage of charged particles ionising a material as they pass through it, as well as the ability of some materials to emit light at optical wavelengths when excited in this way [22]. This optical-wavelength light, termed the scintillation light, is much easier to measure compared to gamma or X-rays. The energy of the ionising particle is able to be measured, as the amount of scintillation photons produced is related to the energy deposited by the charged particle, as well as its charge and mass [22, 23].

As neutrons are uncharged, they interact with the scintillation medium through scattering (either elastic or inelastic) and other nuclear reactions [24]. These processes result in one or more recoiling charged particles (e.g. protons, alpha particles, or carbon nuclei) which then ionise the scintillation medium. This chapter outlines the interactions of neutrons and gamma rays with organic scintillators, the theory of the scintillation mechanism in organic scintillators, the photomultipliers used to detect the scintillation light, and finally two techniques used to determine the energy of the incident neutrons.

2.1 Organic scintillators

Fast neutron fields almost always contain gamma rays [7], so the detection of both particles is of interest in the field of neutron spectroscopy. Both particles, however, are uncharged, so they are detected in scintillators through secondary interactions only.

2.1.1 Neutron interactions with organic scintillators

Neutrons primarily interact with organic scintillators in two ways: elastic scatter of neutrons with hydrogen and carbon nuclei; and α -particle production through neutron reactions with carbon [25]. Figure 2.1 shows the microscopic cross sections for these processes between 1 MeV and 20 MeV, with all other processes contributing negligible amounts.

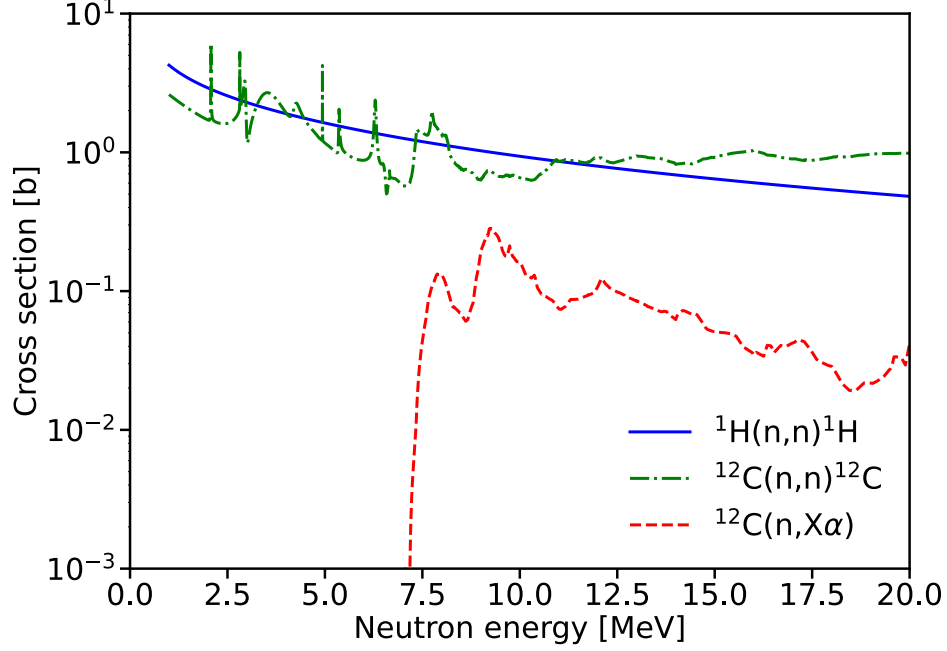


Figure 2.1: Microscopic reaction cross sections for the elastic scatter of neutrons with hydrogen and carbon, and α -particle production through neutron reactions with carbon [26].

Elastic scattering is the dominant process in the < 20 MeV region. Figure 2.2 shows a diagram of this process for a general recoil nucleus, in the laboratory coordinate system where the target nucleus is at rest. With θ as the angle between the recoil nucleus's path and the projected path of the incident neutron, the kinetic energy E_R of the recoil nucleus is given in [25] by

$$E_R = \frac{4A}{(1+A)^2} (\cos^2 \theta) E_n, \quad (2.1)$$

where A is the mass of the nucleus in atomic units and E_n is the kinetic energy of the incident neutron. The maximum energy that can be deposited is when $\theta = 0^\circ$, where Equation (2.1) becomes

$$E_R = \frac{4A}{(1+A)^2} E_n. \quad (2.2)$$

In the case of the hydrogen nucleus ($A = 1$), up to 100% of the neutron's kinetic energy can be transferred to the proton in a single interaction. For a carbon nucleus, the neutron can only deposit a maximum of 28% of its energy. The neutron can continue to interact with, say, a hydrogen nucleus, and is able to deposit all of its energy. The angular distribution of θ is energy dependent and tends to be peaked at forward and backward scattering for fast neutrons, such as in Figure 2.3 for 5.54 MeV neutrons incident on ^4He nuclei [25].

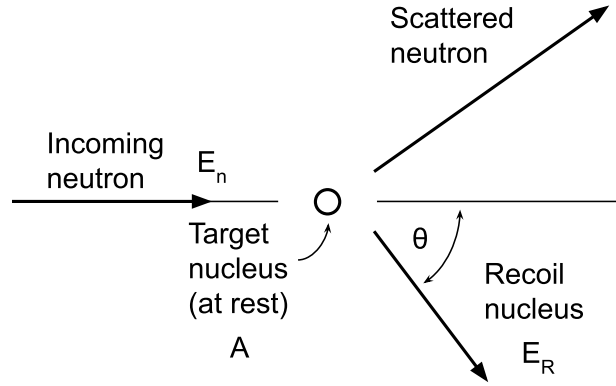


Figure 2.2: Diagram representing elastic scattering of a neutron on a target nucleus at rest, pictured in the laboratory coordinate system [25].

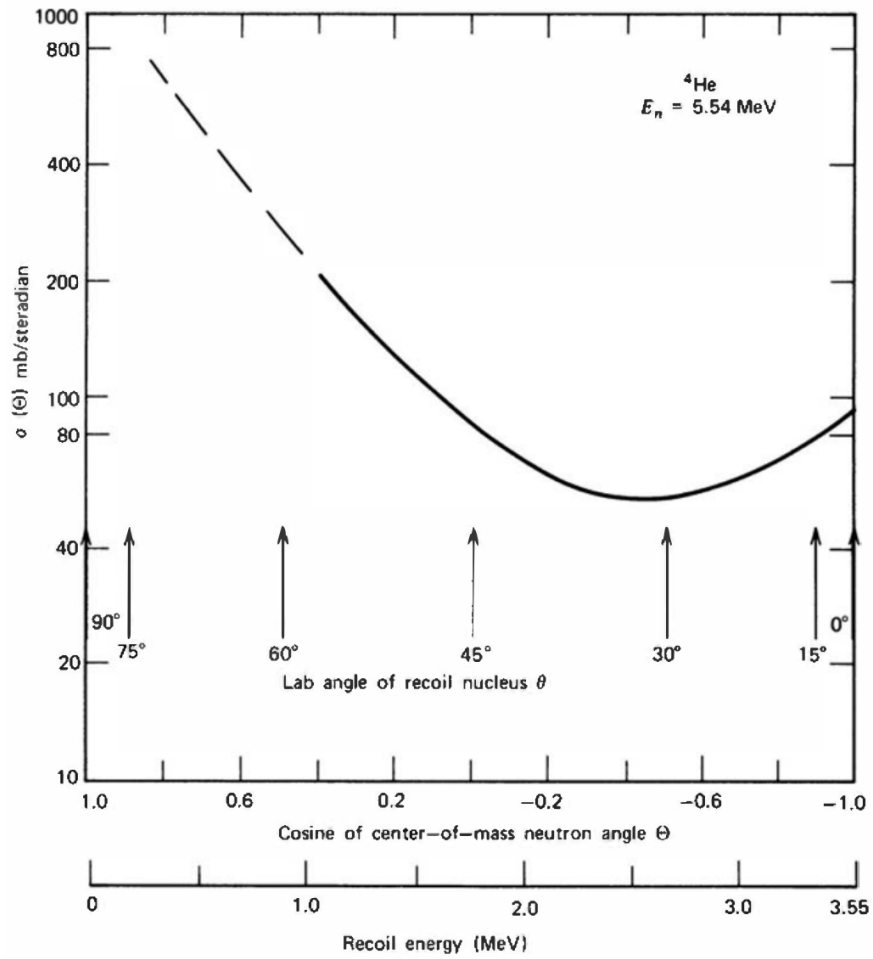
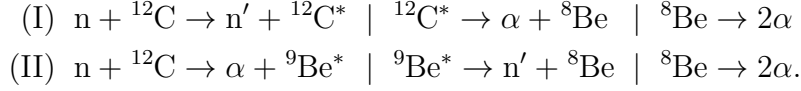


Figure 2.3: Differential cross section as a function of recoil angle for 5.54 MeV neutrons incident on ^4He nuclei [25].

The last relevant process is α -particle production, which is possible for neutron-induced reactions on carbon for energies above 6.19 MeV. This can result in an α -particle and ^9Be nucleus. Above 8.29 MeV and 8.81 MeV respectively, the following two reaction mechanisms, resulting in three alpha particles, also become possible [27]:



2.1.2 Gamma ray interactions with organic scintillators

Gamma rays interact with matter through one of three mechanisms: photo-electric absorption, Compton scattering, and pair production [24]. For organic scintillators and incident energies below $\sim 1\text{ MeV}$, gamma rays interact primarily through Compton scattering, as the cross sections for photo-electric absorption and pair production are very low for low Z nuclei or zero, respectively. Figure 2.4 shows a diagram of the Compton scattering process for an incident gamma ray of energy $h\nu$.

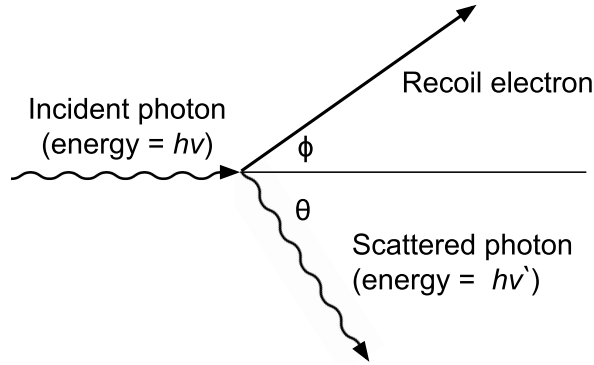


Figure 2.4: Diagram representing the Compton scattering process for a gamma ray with energy $h\nu$ incident on an atom [24]. The recoil electron will have energy equivalent to the difference in incident and scattered photon energy.

The recoil electron will have energy E_e equivalent to the difference in incident (E) and scattered photon energy, given by [24]

$$E_e = \frac{E^2}{E + \frac{m_e c^2}{1 - \cos \theta}}, \quad (2.3)$$

where θ is the angle of the scattered gamma ray relative to the incident gamma ray as in Figure 2.4 and $m_e c^2$ is the rest mass energy of the electron, i.e. 511 keV. The maximum energy of the recoiling electron is called the Compton edge energy, given by

$$E_e = \frac{2E^2}{2E + m_e c^2}. \quad (2.4)$$

Regardless of the process, both neutron and gamma ray interactions result in a recoiling charged particle – protons, carbon nuclei, or alpha particles for neutrons; and electrons for gamma rays. As these recoiling particles travel through an organic scintillator, they deposit their energy by exciting organic molecules with so-called π -electron structures [28]. This structure has an energy spacing between the ground and first excited states on the order of 3–4 eV, with the spacing between higher-lying states being considerably smaller. Excitations of these molecules are either to the first excited state, or they are excited to higher states and undergo radiationless internal conversion to the first excited state, after which the molecule will de-excite by emission of a scintillation photon with wavelength on the order of 400 nm. This is called “prompt fluorescence”.

Many molecules will be excited by a single recoiling particle, resulting in many scintillation photons being emitted. The total number of photons produced by an incident charged particle, termed the light output, is related to the scintillation efficiency of the material (how many photons are emitted per unit energy deposited) as well as the specific energy loss of the particle in the scintillator [28]. The specific energy loss is described by Birks’ relation and is dependent on the charge and mass of the particle [23]. Figure 2.5 shows the scintillation response of anthracene to various charged particles. For all particles, the response is nonlinear below some value, and then becomes linear as energy increases.

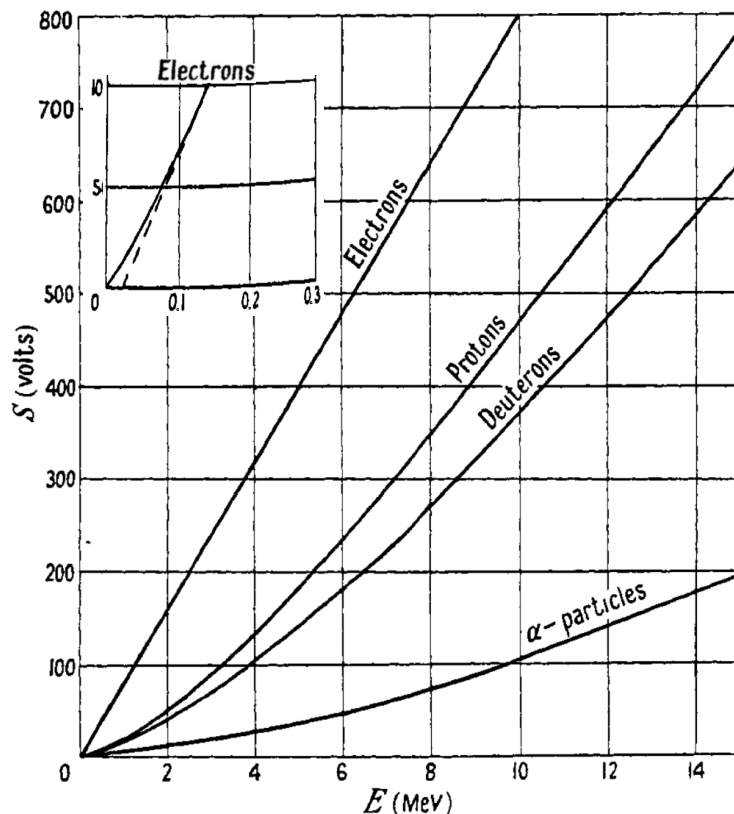


Figure 2.5: Relative scintillation response S of anthracene to particles of energy E [23]. Inset is the scintillation response to low energy electrons.

As well as producing fewer scintillation photons per unit energy deposited, heavier recoil charged particles also produce a slightly different scintillation response with respect to the timing of the production of scintillation photons. When a molecule in the π -electron structure is excited by an ionising particle, there is a chance that it can undergo “intersystem crossing”, whereby it changes to a nearby state with a much longer characteristic lifetime. Thermal excitations convert this state back to the first excited state, which then decays as usual, producing a photon. The light produced in this way is termed “delayed fluorescence” as the thermal excitations are not instantaneous. There is always some component of delayed fluorescence in the light output of a charged particle, but the amount relative to the prompt fluorescence is proportional to the energy loss dE/dx of the particle, which itself is dependent on both charge and mass. This is seen in Bethe-Bloch [29]

$$\frac{dE}{dx} = \frac{4\pi e^4 q^2}{m_e c^2 \beta^2} N Z \left[\ln \left(\frac{2m_e c^2 \beta^2}{I \ln(1 - \beta^2)} \right) - \beta^2 \right], \quad (2.5)$$

where q is the charge of the particle, $\beta = v/c$ is the usual ratio of velocity to the speed of light, N is the number density of the molecules in the medium with atomic number Z , e is the electron charge, I is an empirical constant for the medium, and m_e is the electron mass. In this way, different recoiling particles can be discriminated by examining the ratio of delayed to prompt fluorescence. A practical implementation of pulse shape discrimination (PSD) is discussed in Section 2.3.2.

Since organic scintillators work on a molecular level [28], in contrast to crystalline scintillators such as NaI where a regular lattice is needed, the scintillating medium can take a variety of physical forms. For example, EJ-301 liquid organic scintillator is an industry standard in the field of neutron metrology as it provides excellent energy resolution as well as the ability to discriminate between neutrons and gamma rays. However EJ-301 is toxic and volatile, requiring encapsulation in a glass and aluminium container. For applications requiring large volumes of scintillating material, plastic scintillators such as EJ-200 are often used as they can be cast into large slabs and photodetectors can be placed at any point on the geometry.

Historically, plastic scintillators have not been used for neutron spectroscopy for two main reasons: particle discrimination was not possible and the energy resolution of detectors made with plastic scintillators was poor compared to their liquid counterparts [30]. In the past 15 years, however, there has been steady development of a new plastic scintillator that is both capable of particle discrimination and shows good energy resolution. Eljen Technologies first produced EJ-299-33, before developing EJ-276 [17], the material used in this work. A comparison in the scintillation properties is shown in Table 2.1.

2.2 Photomultipliers

A traditional photomultiplier tube consists of a glass vacuum tube with a number of electrodes inside, named “dynodes”. On one end of the tube is the photocathode, a thin layer of a material that emits an electron when a photon is incident upon it. The electron is accelerated in a large electric field generated within the tube and strikes the first dynode,

Table 2.1: Scintillation properties of the EJ-276 plastic scintillator [17] and EJ-301 liquid scintillator [31].

Property	EJ-276	EJ-301
Light output (% Anthracene)	56	78
Scintillation efficiency (photons/MeV _{ee})	8600	12000
No. of H atoms per cm ³ ($\times 10^{22}$)	4.647	4.82
No. of C atoms per cm ³ ($\times 10^{22}$)	4.944	3.982
No. of electrons per cm ³ ($\times 10^{23}$)	3.545	2.27

which causes multiple electrons to be emitted, which all travel towards the next dynode, and the cycle repeats. Dynodes are typically held at potentials of hundreds of volts and produce around five secondary electrons per primary. With a typical twelve dynodes, a single incident photon can produce over 2×10^8 electrons at the final dynode, also called the anode [32]. Photomultiplier tubes are used to detect the scintillation photons and multiply the signal so that it can be amplified and processed by the electronics.

2.2.1 Silicon photomultipliers

Silicon photomultipliers (SiPMs) are a more recent addition to the world of photomultipliers [33, 34] and while the technology is solid state, the concepts are practically the same. The photomultiplier is made of an array of photodiode microcells, shown in Figure 2.6. An incident photon will excite an electron in the photodiode from the valence band to the conduction band, producing an electron-hole pair. The region where these pairs are created is also known as the “depletion region”. With a bias applied between the anode and cathode, the electron and hole will drift towards their respective electrode [35]. Silicon photomultipliers are often used in this way for single photon counting, but for the purposes of capturing scintillation light, another mode of operation is used.

If the bias applied between the anode and cathode (and thus the individual depletion regions) is high enough ($> 5 \times 10^5 \text{ V cm}^{-1}$), the SiPM is said to be in “Geiger mode”. In practice this is when the bias applied to the SiPM is above the “breakdown voltage”, which varies depending on the design of the SiPM. The high electric field accelerates the electron and hole to such an extent that secondary charge pairs are created through a process called impact ionisation. This continues in an avalanche.

When in Geiger mode, the avalanche reaction in each microcell could continue indefinitely, so a quenching process is required in order to stop the chain reaction. This is usually achieved with passive quenching, where a resistor is placed in series with the photodiode, as seen in Figure 2.6. The silicon in the depletion region breaks down and becomes conductive during the avalanche, effectively resulting in macroscopic current flow. Once the current is flowing, it needs to be stopped. The resistor causes a voltage to be set up in opposition

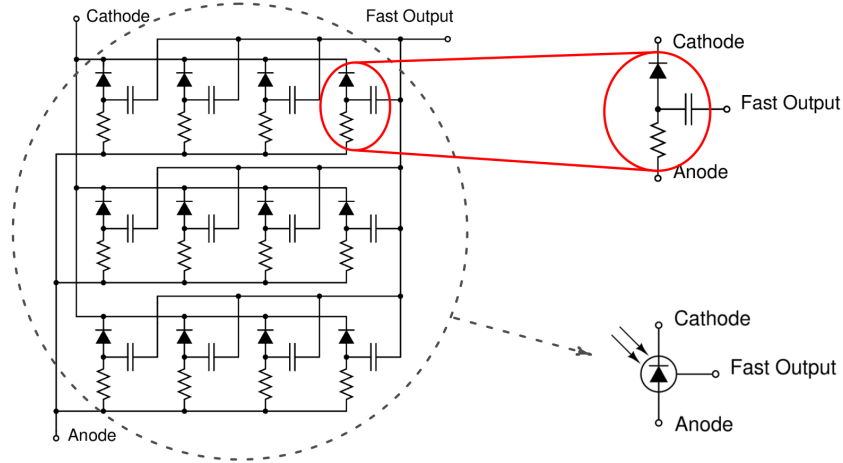


Figure 2.6: Circuit diagram of a number of microcells in a silicon photomultiplier. The diode in each microcell is the sensitive area [35].

to the applied bias, lowering the effective electric field across the photodiode such that the avalanche is halted. The photodiode then recharges back to the bias voltage and is able to detect photons again. By this process, the output of each microcell is approximately equal, so the SiPM output, which is a sum of the microcell outputs, is proportional to the number of photons that were incident on the SiPM surface.

Since this quenching process takes some time (on the order of nanoseconds), there is an inherent nonlinearity in the output of the SiPM when subject to high rates as multiple photons interacting with a microcell within the time taken to quench and reset will look like a single interaction with respect to the output of the SiPM. The nonlinearity is well understood and is described in [35] by

$$N_{\text{fired}} = M \left(1 - e^{\frac{-N_{\text{ph}} \cdot \text{PDE}}{M}} \right), \quad (2.6)$$

where N_{fired} is the number of microcells that produce a signal, M is the number of microcells in the SiPM array, N_{ph} is the number of photons incident on the entire array, and PDE is the photon detection efficiency of a given microcell, usually on the order of 10 – 20%.

When operating in Geiger mode, thermal excitations in the materials inside the microcells will produce electrons that can lead to an avalanche and thus a detectable change in voltage. This background noise is called the dark count rate (DCR) and is a function of active area, overvoltage, and temperature. For applications where single photon counting is not of interest, such as in scintillation counting, the bias voltage is typically set 10 – 25% higher than the breakdown voltage to increase the gain of the output signal. However, increasing the voltage also results in a proportional increase in noise and DCR. For these applications the detection threshold can simply be set above the DCR noise. The difference between operating and breakdown voltage is termed the “overvoltage”. Figure 2.7 shows an example of a voltage pulse from a SiPM as a result of a pulsed light source about 1 cm from the sensor. The noise associated with the DCR can be seen on the baseline in the first 50 ns.

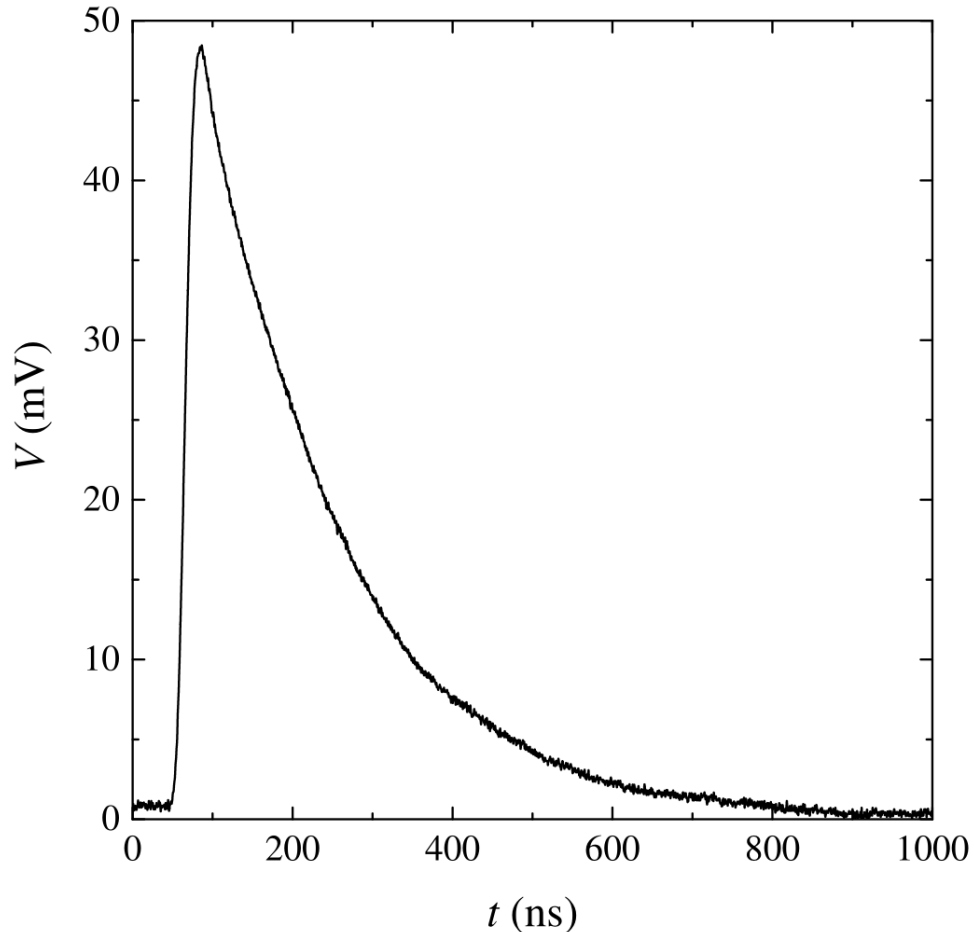


Figure 2.7: A typical digitised signal from a pulsed light source approximately 1 cm from a SiPM, with an overvoltage of 2 V [13].

2.3 Pulse processing

Once the scintillation light has been detected by the photomultiplier and an output signal created, it must be processed to determine the energy deposited by the recoiling particle, and in some cases the type of recoiling particle itself.

2.3.1 Light output units

Each radiation-induced event in the detector is associated with recoiling charged particles depositing energy in the medium, thus creating scintillation light which, through the processes described above, becomes a voltage pulse, such as that shown in Figure 2.7.

There are a few ways of extracting a measure of the energy deposited from the corresponding voltage pulse but in this work the integral of the pulse is used as it is proportional to the total charge produced in the photomultiplier and thus the number of scintillation photons. As discussed previously, the number of scintillation photons produced depends on the specific energy loss of the recoiling particle, which depends on the mass of the particle. Thus, a

1 MeV electron depositing all of its energy will produce more scintillation photons than an equivalent proton. The light output parameter is defined as

$$Q_L = \int_{t_0}^{t_L} V(t)dt, \quad (2.7)$$

where $V(t)$ is the voltage as a function of time and t_0 and t_L are the start and end points of the integral, usually set to include as little baseline before the pulse begins and to end after the pulse has returned to the baseline. This Q_L will be smaller for a proton than an electron, for the same incident energy. For organic scintillators, the Compton edge positions associated with known gamma ray energies are used to calibrate Q_L to a measure of the energy deposited by the recoiling particle, called L . Thus for electrons L is equivalent to the deposited energy, however for heavier particles it is called the “electron equivalent” energy, or MeV_{ee} .

2.3.2 Pulse shape discrimination

In this work, the charge comparison method is used to discriminate between neutron and gamma ray events, where each event pulse is integrated over a long and a short time interval and the ratio taken to be the pulse shape parameter [36]. Since heavier charged particles are expected to have a larger proportion of delayed to prompt fluorescence, the ratio of the two integrals is expected to change depending on the type of recoiling particle. Figure 2.8 shows typical neutron- and gamma ray-induced event traces for the same long integral after baseline subtraction. Clearly, gamma ray-induced events result in a larger component of the pulse within the short integral window.

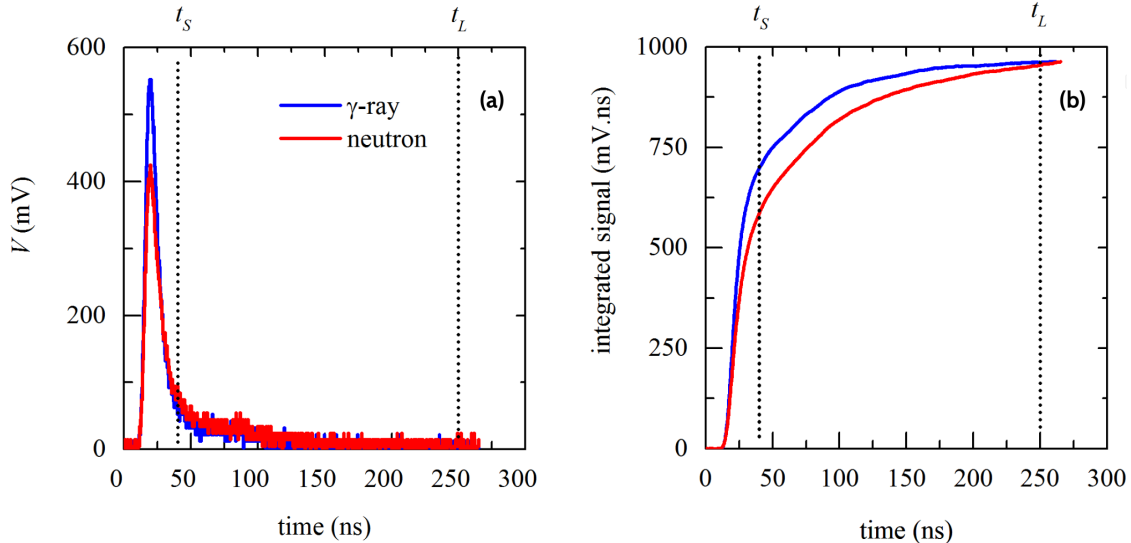


Figure 2.8: Typical digitised pulses (a) and their cumulative pulse integrals (b) for events arising from neutron (recoil proton) and gamma ray (recoil electron) interactions in an EJ-301 scintillator coupled to a PMT. The pulses were selected to have the same long integral. The short and long integration times are shown [13].

The ratio S , given by

$$S = \frac{\int_{t_0}^{t_S} V(t)dt}{\int_{t_0}^{t_L} V(t)dt} = \frac{Q_S}{Q_L}, \quad (2.8)$$

where t_S and t_L are the short and long integral times as shown in Figure 2.8 and t_0 is defined as in Equation (2.7), is called the pulse shape parameter. Figure 2.9 shows an example plot of the result of calculating S for each event and comparing it to the light output L , for events detected by a sample of EJ-276 plastic scintillator coupled to SiPMs, generated by a D-T sealed tube neutron generator producing 14.1 MeV neutrons and a broad spectrum of gamma ray energies produced from neutron interactions in the surrounding materials. Two clear loci can be seen, with the top corresponding to gamma rays and the bottom to neutrons. Cuts can be made on these data in software or hardware by specifying a value of S below which all events are considered neutrons. Due to the shape of the distribution, this value of S depends on L , as shown by the dashed line in Figure 2.9.

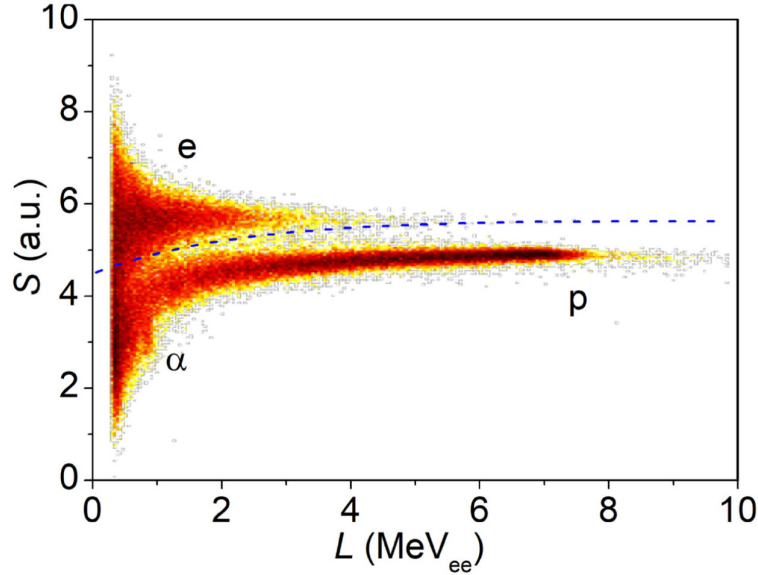


Figure 2.9: A typical PSD distribution for events from a D-T sealed tube neutron generator, producing 14.1 MeV neutrons and broad spectrum gamma rays [37]. Shown is counts as a function of light output parameter L and pulse shape parameter S for events in a sample of EJ-276 coupled to SiPMs. The labels indicate event distributions associated with recoiling electrons (e), protons (p), and alpha particles (α). A cut to discriminate neutron and gamma ray events is shown (blue dashed).

2.3.3 Light output spectra

Once events have been attributed to gamma ray or neutron interactions, the light output spectrum for each can be determined by histogramming all events of a certain type according to L as determined in Equation (2.7). Gamma ray light output spectra are simply the combination of the Compton continua associated with each of the unique gamma ray energies that compose the field, such as in Figure 2.10, where the light output spectrum associated with a ^{22}Na gamma ray source is shown. The Compton continuum associated with the 511keV gamma ray is superimposed upon that of the 1274keV gamma ray. Above $\sim 1.2\text{MeV}$, pair production becomes possible and can also contribute to measured gamma ray light output spectra.

Neutron light output spectra are composed of contributions from any recoiling particle other than an electron. Figure 2.11 shows a neutron light output spectrum, measured by an NE-213 organic scintillator coupled to a PMT (histogram) as well as a Monte Carlo simulation (M), which is composed of responses to various recoiling particles (A-E) for monoenergetic 14.1 MeV neutrons. Component A is due to n-p elastic scattering of primary neutrons. Components B and C are due to the $^{12}\text{C}(n, \alpha)^9\text{Be}$ and $^{12}\text{C}(n, 3\alpha)n'$ reactions respectively. Components D and E are due to n-p elastic scattering of neutrons after they have been degraded by elastic and inelastic scattering on carbon respectively. It can clearly be seen that elastic scatter on hydrogen is the dominant process in this neutron light output spectrum, a trend which is true for the entirety of the $< 20\text{MeV}$ region.

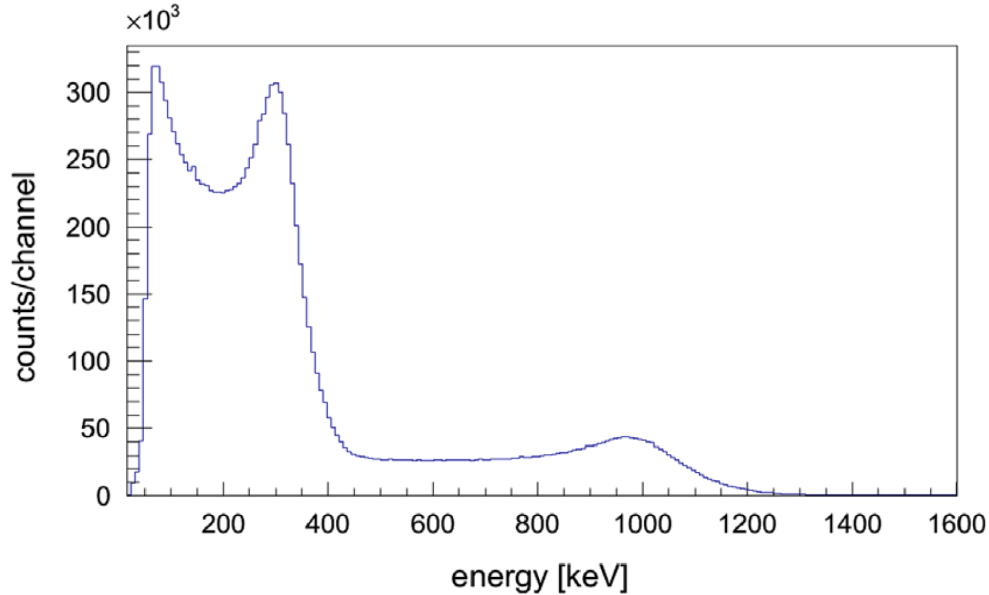


Figure 2.10: Typical pulse height spectrum from a ^{22}Na source measured by EJ-299-33 plastic scintillator coupled to a PMT [30].

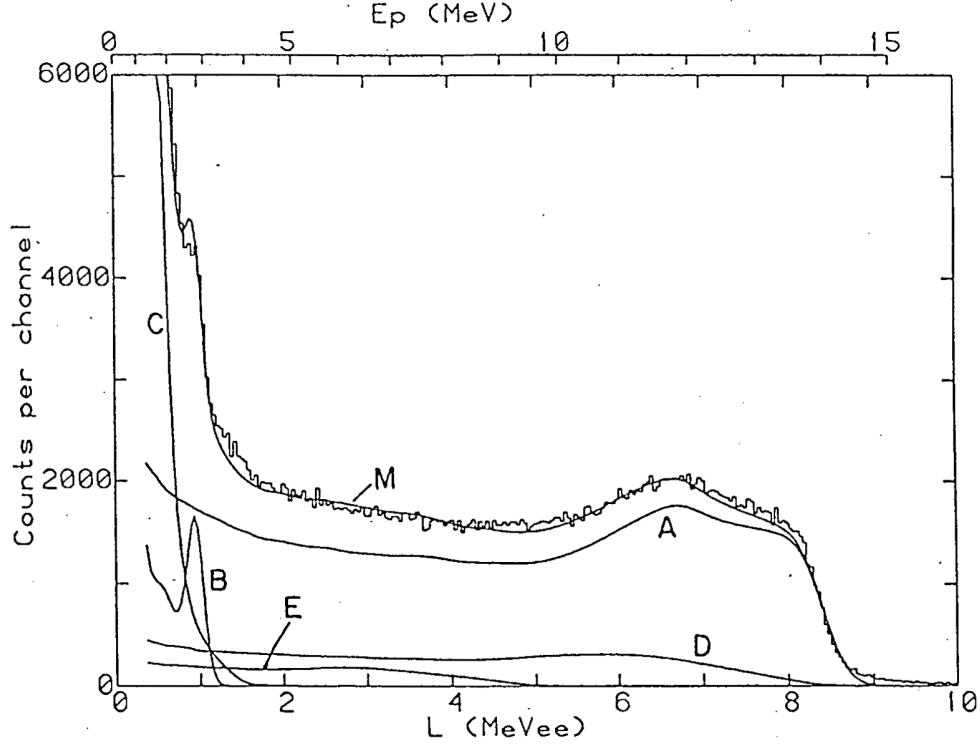


Figure 2.11: Response function of an NE-213 detector ($130\text{ mm} \times 130\text{ mm} \times 70\text{ mm}$), coupled to a PMT, to 14.1 MeV neutrons, showing experimental measurement (histogram) and Monte Carlo simulation M made up of components A-E [38].

2.4 Neutron spectroscopy

2.4.1 Time-of-flight

The time-of-flight technique is the gold-standard for neutron spectroscopy. By timing how long a neutron takes to travel from its point of production to the point of detection, the energy can be determined using simple kinematics [39]. In practice, neutrons are produced by accelerating charged particles, such as protons or deuterons towards a target containing a material that the charged particle will react with, such as tritium, deuterium, or beryllium. The accelerated particle and the target material undergo a reaction, which causes a neutron to be ejected. The energy of the ejected neutron depends on the energy of the incident particle as well as the angle at which it is ejected relative to the incident beam.

The particles are accelerated towards the target at regular intervals and the accelerator produces a signal each cycle (called the RF pulse) that can be measured alongside any detector trace. The detector is placed at a distance d away from the target. The time taken for the neutron to reach the detector T can thus be measured and the kinetic energy of the neutron E_n found with

$$E_n = m_n c^2 \left(\frac{1}{\sqrt{1 - \frac{d^2}{T^2 c^2}}} - 1 \right), \quad (2.9)$$

where m_n is the mass of the neutron and c is the speed of light.

Of course, this technique requires a highly specialised accelerator facility, thus it is impossible to implement in workplace environments such as those of interest in this work. For this reason, another technique is used to determine the neutron energy spectrum associated with a measurement.

2.4.2 Unfolding

The dominant component of a neutron light output spectrum for the < 20 MeV region is elastic scattering of neutrons with hydrogen. As the angle that the hydrogen nucleus is scattered at for a given event is not necessarily knowable, the energy of the incident neutron cannot be determined on an event-by-event basis. Thus, in order to determine the energy of the neutrons incident on the detector, a technique called spectral unfolding is used [40].

The basis of the technique is an assumption that a measured light output spectrum corresponding to an arbitrary energy spectrum of incident neutrons is a linear combination of light output spectra corresponding to monoenergetic neutrons, given by

$$z_i = \sum_{j=1}^m R_{ij} \phi_j. \quad (2.10)$$

Here z_i is the number of events in bin i for the measured light output spectrum, ϕ_j is the fluence of incident neutrons of a given energy indexed by j , and R_{ij} is the intensity of channel i of the light output response associated with one incident neutron of energy j normalised per unit fluence at the centre of the detector. Spectrum unfolding is the process of deconvolving Equation (2.10) to find the energy spectrum ϕ of the neutrons incident on the detector. A close examination of Equation (2.10) reveals that the energy resolution of the unfolded energy spectrum depends on the energy spacing of the measured light output responses, i.e. more densely packed responses can result in better energy resolution, provided the light output resolution is good and each response is sufficiently unique.

The unfolding technique thus requires a set of measured light output responses R_{ij} associated with incident monoenergetic neutrons. Of course these can be obtained by measuring the response of many different monoenergetic neutron fields, but another method is to irradiate

the detector with neutrons of a wide range of energies, often called broad-spectrum or a “white” source, and sort events in post-processing according to the incident neutron energy, producing nearly monoenergetic responses. In order to determine the energy of the neutron, the time-of-flight technique is used such that the energy of each event is known and the light output response for the entire measurement can be split into responses corresponding to slices in incident neutron energy [37].

Chapter 3

Development of the detector system

The design of the detector system was influenced by two key requirements: the ability to operate outside of laboratory environments; and insensitivity to the direction of the incident radiation in terms of detector response.

3.1 The n-lab

The n-lab is a fast neutron facility within the Metrological and Applied Sciences University Research (MeASURe) Unit in the Department of Physics, University of Cape Town (UCT) [41]. The facility features a Thermo Scientific MP-320 sealed tube neutron generator (STNG) and a 220 GBq radioisotopic ^{241}Am - ^9Be (AmBe) source. The sources are housed in a vault of high density polyethylene (HDPE) pellets and blocks as shielding, with a $\varnothing$ 17.5 cm collimator extending the beamline into the experiment area. Additional HDPE collimators can be placed within this to further shape the beam. The layout is illustrated in Figure 3.1. The reference detector for fast neutron measurements is a $\varnothing$ 5 cm $\times$ 5 cm cylindrical EJ-301 organic liquid scintillator [31] coupled to a 12-stage PMT, which is permanently installed in the experimental area, on a motion stage. Detectors of interest can be positioned in the experimental area in front of the reference detector.

The STNG accelerates deuterons onto a TiT target, which produce neutrons in all directions via the $^3\text{H}(\text{d}, \text{n})^4\text{He}$ fusion reaction. Neutrons produced perpendicular to the deuteron beam have an energy of 14.1 MeV [42] and are collimated into the experimental area. Gamma rays of energy 2.2 MeV and 4.4 MeV are also produced by neutron capture on hydrogen and in elastic scatter of neutrons on carbon in the HDPE shielding, respectively. The STNG was used as a source of monoenergetic neutrons, in order to evaluate the light output resolution of the detector system.

The ^{241}Am in the AmBe source is an α -particle emitter with a half life of around 430 years. The alpha particles react with the ^9Be to form $^{12}\text{C} + \text{n}$, with the ^{12}C likely to be in an excited state. The neutron can be emitted with a range of energies, from thermal to $\sim$ 11 MeV, and the ^{12}C de-excites by emission of a 4.4 MeV gamma ray from the first

excited state [43]. Neutron energy spectra for the neutron generator and AmBe source are shown in Figure 3.2.

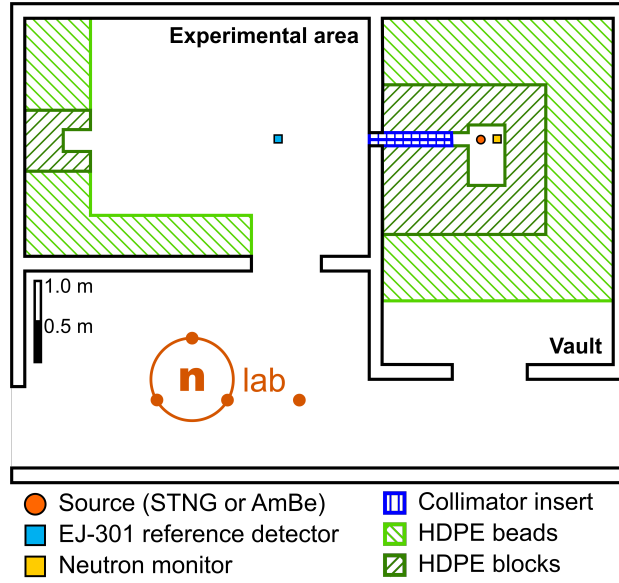


Figure 3.1: Schematic of the n-lab facility at UCT. Shown is the neutron vault, experimental area, and control room [41].

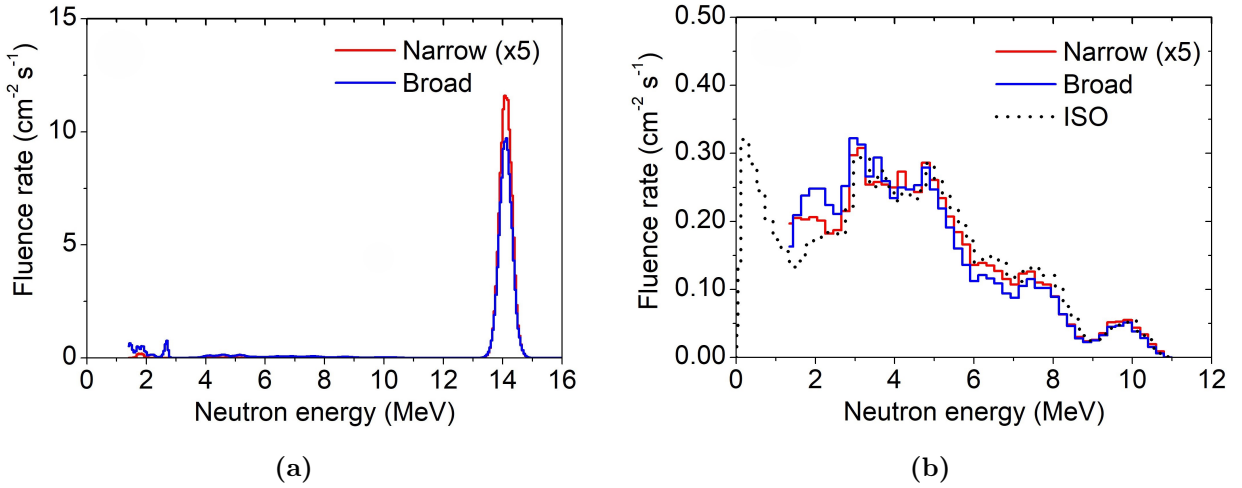


Figure 3.2: Measured energy spectra of the (a) STNG and (b) AmBe source at the n-lab, using the broad and narrow collimators [41]. The AmBe spectrum is compared to the ISO standard [44].

3.2 Design

The scintillator type chosen for this work is EJ-276: a PSD-capable plastic scintillator material produced by Eljen Technologies [17] that has been studied extensively and been proven to perform well over a wide range of neutron energies [37, 45–47]. The plastic

scintillator produces less light output than a standard organic liquid scintillator such as EJ-301 ($\sim 72\%$ of the scintillation photons produced per 1 MeV deposited by an electron) [17]. The lower light output of the plastic scintillator will ultimately result in a reduced energy resolution but this is a worthy trade-off for the convenience of easy machining and safety of use compared to the liquid scintillator. The wavelength of the scintillation light produced by this material peaks at 425 nm, with the spectrum shown in Figure 3.3.

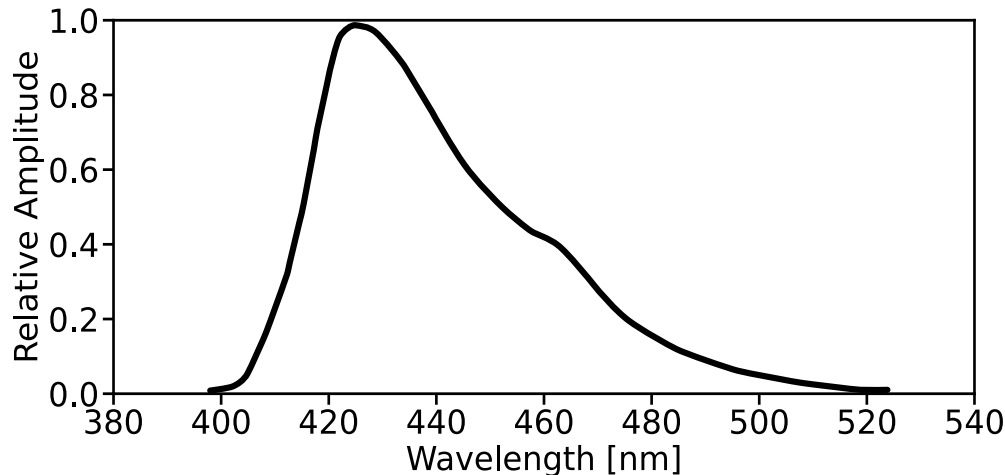
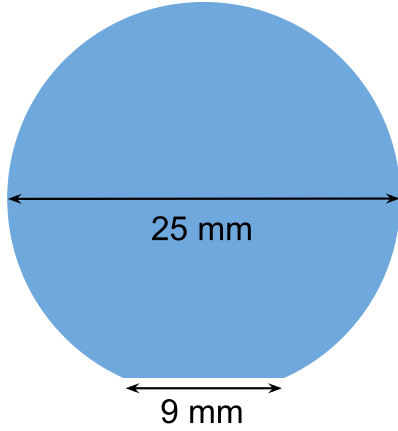


Figure 3.3: Scintillation emission spectrum for EJ-276 adapted from [17].

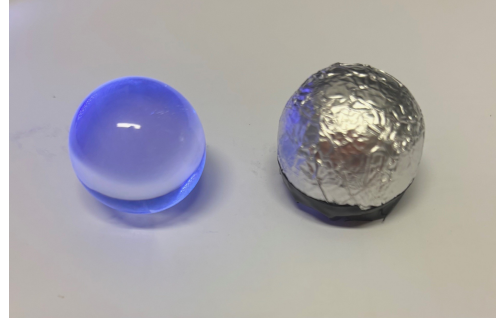
The scintillator can be purchased in cylindrical or slab forms and can be easily machined. Traditionally, scintillators used for spectroscopy have a cylindrical shape as that is well matched to the cylindrical photomultiplier tubes that are most commonly used. For this development, however, a spherical shape was used. The scintillation light must, however, be collected somewhere, so the chosen design was a $\varnothing$ 25 mm sphere with a $\varnothing$ 9 mm flat zone to allow for direct coupling to a silicon photomultiplier, as shown in Figure 3.4. The sphere was machined from a $\varnothing$ 25.4 mm stock cylinder at the mechanical workshop within the Department of Physics at UCT.

Scintillation light is emitted isotropically from the point of interaction of the charged particle, so the scintillator needs to be wrapped in some kind of reflective material to allow the light to scatter and eventually reach the photomultiplier. In some cases a specular reflector is used [37], particularly for scintillators with a flat surface opposite to the photomultiplier, however in the case of the spherical scintillator a diffuse reflector was chosen to allow for any light reaching the boundary to scatter in a random direction. For some diffuse reflectors such as paper, the material cannot be moulded to perfectly fit the sphere. So, where there are small air gaps between the scintillator and reflector and provided the angle of incidence is large enough, there is total internal reflection and it acts as a specular reflector.

In order to avoid this effect, PTFE tape was chosen as the wrapping material as it conforms easily to the shape of the scintillator and forms a good optical connection. Several uniform layers were required to produce an opaque surface, which was checked by illuminating the scintillator with a UV light source. After wrapping with PTFE tape, the sphere was wrapped in aluminium foil and then electrical tape to bind everything together.



(a)



(b)

Figure 3.4: (a) Side-on schematic of the sphere of EJ-276 produced for this work with a flat region for coupling to a silicon photomultiplier. (b) The machined sphere of EJ-276 scintillator along with its foil wrapping, inside of which is the PTFE tape wrapping.

The MicroFC-60035 C-Series silicon photomultiplier from onsemi [48] has a $6\text{ mm} \times 6\text{ mm}$ sensitive area and can be run in Geiger mode when operated above the breakdown voltage of $+25\text{ V}$. Custom PCBs were designed by the electronics workshop within the Department of Physics at UCT (shown in Figure 3.5) to extract only the standard output. The “fast” output was not used as the timing information relevant to PSD is lost in order to provide a signal that can be used for triggering if necessary. The SiPM was operated at $+28.5\text{ V}$ as a balance between an increase in gain and an increase in background noise as a result of an increasing dark count rate with overvoltage. This voltage was found to be optimal for these sensors in previous work at the n-lab [16]. The connectors on the SiPM board are MCX connectors.

The scintillator was optically coupled to the SiPM with EJ-550 silicone optical grease produced by Eljen Technologies. In order to hold the SiPM and scintillator together, an aluminium case was manufactured by the mechanical workshop, shown in Figure 3.6(a). It consists of a square bottom dish with holes in two sides to allow the SiPM connectors to pass through, while locating the SiPM at the centre of the case. The top piece slides down, with another two holes in the same position, and three bolts screw through the top piece into threaded holes in the bottom, at three of the corners. The top piece has a domed lid to allow for the sphere to be padded with foam to secure it in place and protect against mechanical shocks. The sphere and SiPM are held in position by 3D-printed spacers and small rubber o-rings slide onto the connectors before being inserted into the case to reduce light leakage. The front face of the detector is considered to be the tip of the dome on the top casing.

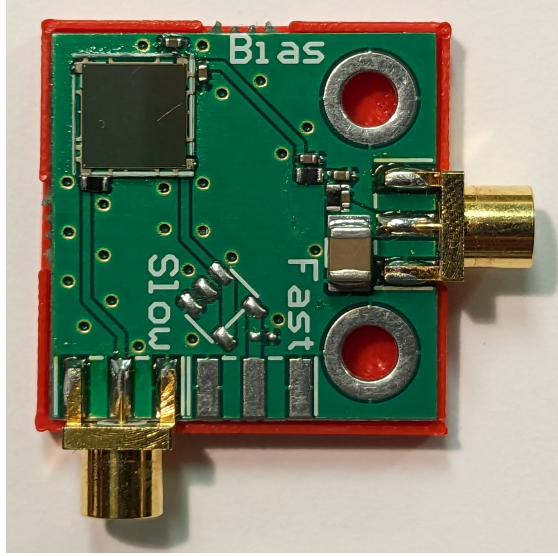


Figure 3.5: MicroFC-60035 C-Series silicon photomultiplier from onsemi mounted on a custom-made PCB, using only the standard output (labelled here as “slow”) at the bottom of the board. Bias is applied via the right-hand connector.

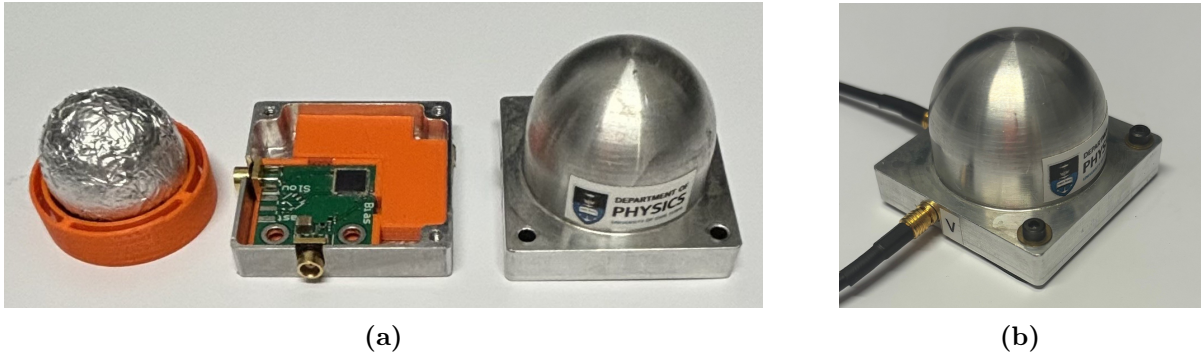


Figure 3.6: (a) The detector system deconstructed. From left to right: wrapped sphere in 3D-printed collar; SiPM board in bottom casing with spacers; top casing. (b) The constructed detector system with cables attached.

Pulses from the detector were acquired by a CAEN DT5730S desktop digitiser [49] connected to a PC running custom open-source acquisition software QtDAQ [13], which was developed at UCT. The DT5730S digitiser, shown in Figure 3.7, is an 8-channel, 14-bit digitiser with a sampling rate of 500 MS/s with a programmable voltage range of either $0.5 V_{pp}$ or $2.0 V_{pp}$.

The digitiser triggers on an absolute voltage crossing threshold, which can be set in a configuration file, and can trigger on any one of the channels, prompting all channels to acquire simultaneously. Once triggered, the digitiser captures the pulses in a programmed window length, with some programmed pre-trigger length. The digitiser interacts with the PC and QtDAQ [13] over either a USB-2.0 connection or an Optical Link with an



Figure 3.7: The CAEN DT5730 desktop digitiser [49].

A3818 PCI-e CONET2 controller. The pulses were acquired in list mode and then processed post-acquisition using a series of custom-built Python scripts.

3.3 Initial characterisation at the n-lab

Before taking the detector system to metrology facilities to measure response functions, a number of preliminary analyses were performed at the n-lab.

3.3.1 Gamma ray calibration of light output to energy

For neutron measurements in this work, a gamma ray calibration is necessary to provide a reference scale between facilities. Figures 3.8 and 3.9 show an example gamma ray calibration undertaken at the n-lab, used to calibrate measurements of an AmBe source. All gamma ray calibrations used in this work follow a similar structure. Monoenergetic gamma ray sources are ideal for this calibration, such as ^{137}Cs and ^{54}Mn , but other sources such as ^{22}Na , with two distinct gamma rays, are also commonly used.

For this measurement, ^{137}Cs , ^{54}Mn , and ^{22}Na were used, providing four distinct gamma rays. The light output spectrum was measured for each source, with the light output parameter Q_L determined as described in Section 2.3.1 for a long integration time of 1300 ns. Figure 3.8 shows the uncalibrated light output spectrum in black measured for a ^{137}Cs source. Compton scattering is the dominant process, so the Compton edge was used as the reference point for a given gamma ray energy. For the gamma ray from ^{137}Cs , the Compton edge energy is 447 keV.

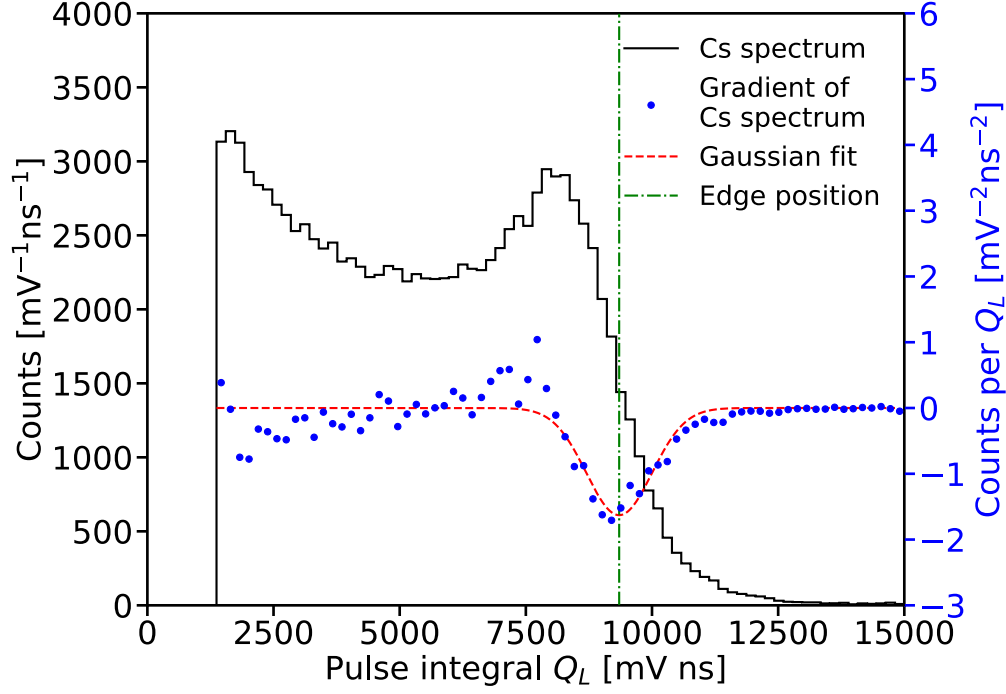


Figure 3.8: Light output spectrum measured for a ^{137}Cs radioisotopic gamma ray source with a $\varnothing$ 25 mm sphere of EJ-276 coupled to a SiPM. Shown is the spectrum, the derivative of that spectrum, a Gaussian function fit to the gradient, and the centroid value of the fitted Gaussian function.

To find the position of the Compton edge in terms of Q_L , the light output spectrum was differentiated, which produces an inverted Gaussian shape (blue circles in Figure 3.8). A Gaussian function was fit to these data using `scipy.optimize.curve_fit` (red dashed line) and the centroid value taken as the position of the Compton edge (green dot-dashed) [45].

Compton edges were found for each of the primary gamma rays for each source. In the case of ^{22}Na , with two prominent gamma ray emissions, the process is the same as with ^{137}Cs as the continuum for the 511 keV annihilation gamma ray sits on top of the continuum for the 1274 keV gamma ray, and the continua are flat enough to have minimal effect on the process. A source such as ^{60}Co can be used in the same way, but in practice for this detector system the two primary gamma rays are too close in energy to resolve.

The light output as a function of gamma ray energy was assumed to be linear and a weighted linear fit was performed to determine the calibration factor. Figure 3.9 shows the measured Compton edge position in terms of Q_L with the expected edge energy, alongside the linear fit. With this calibration performed, each event's light output as determined by the pulse integral, for the associated AmBe measurement, was converted to L in MeV_{ee} units using these factors.

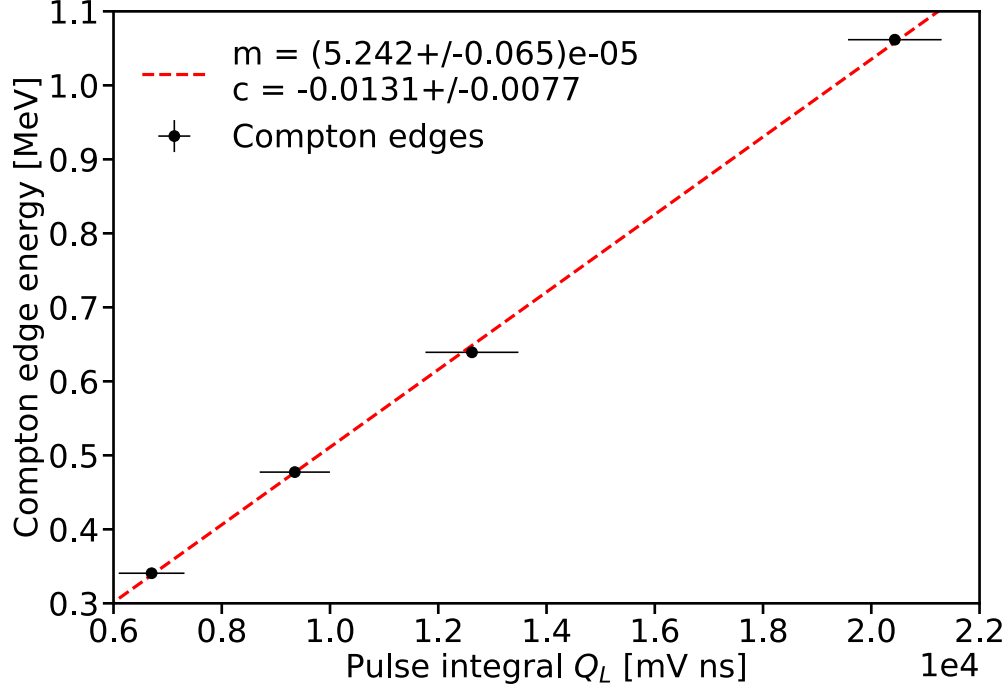


Figure 3.9: Uncalibrated Compton edge positions with their expected edge energies, measured by a $\varnothing$ 25 mm sphere of EJ-276 coupled to a SiPM. Plotted is the weighted linear fit used to determine the calibration parameters. Uncertainties on the Compton edge energies are smaller than the marker.

3.3.2 Pulse shape discrimination with an AmBe source

Pulse Shape Discrimination (PSD) is a procedure used in all fast neutron measurements as fast neutron fields are hardly ever absent of gamma rays [7] and the detectors are often sensitive to both. What follows in this section is an example of the PSD procedure performed on a measurement of an AmBe source at the n-lab, resulting in a neutron light output spectrum, calibrated to MeV_{ee} using the parameters determined in Section 3.3.1. Included is the process used to optimise the integration times.

The charge comparison method of PSD requires the calculation of the parameter S , defined as

$$S = \frac{\int_{t_0}^{t_S} V(t) dt}{\int_{t_0}^{t_L} V(t) dt} = \frac{Q_S}{Q_L}, \quad (3.1)$$

which itself involves the computation of the long (Q_L) and short (Q_S) integrals of the pulse for each event. In practice, the long and short integrals are computed by integrating the voltage values between start and end points defined relative to a reference point on the pulse. The rise time of a pulse is dependent on the energy deposited for that event (larger pulses will have a steeper gradient in the initial phase) so the trigger time, which is simply the time when the voltage goes above a certain threshold, will not be at the same relative position

on each pulse detected. To remedy this, a digital constant fraction discriminator (CFD) is implemented to find a reference point on each pulse.

The CFD pulse is constructed from the original pulse by shifting the original pulse forwards by 6 samples, then subtracting that from the original pulse scaled to 75% of its original amplitude, as shown in Figure 3.10. The “scale” and “shift” parameters were determined by [13] for plastic scintillators mounted on SiPMs.

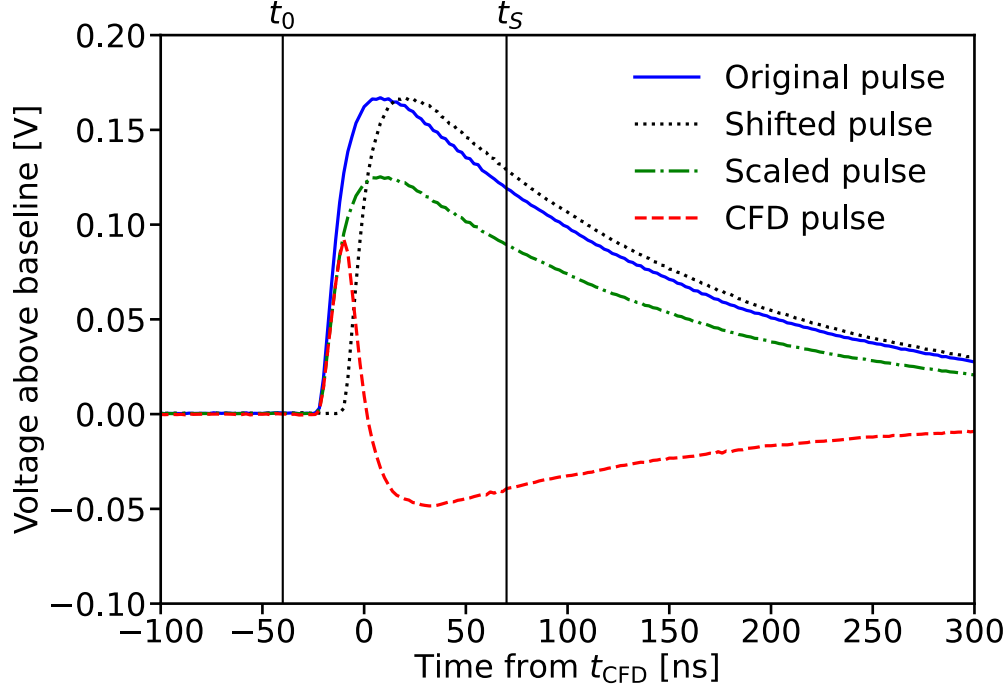


Figure 3.10: An event pulse from a $\varnothing$ 25 mm sphere of EJ-276 coupled to a SiPM along with the steps taken to turn it into a CFD pulse. The time that the CFD pulse crosses the baseline is defined as t_{CFD} . Shown are t_0 and t_S .

The time that the CFD pulse crosses the baseline (t_{CFD}) is the reference point according to which the integral lengths are defined. In practice, t_{CFD} is taken to be the digitiser sample before the crossing event. The integrals start at some defined time t_0 before t_{CFD} and end at some time t_S or t_L after t_{CFD} , as shown in Figure 3.11. A time of -40 ns was chosen for t_0 as it does not exclude the start of even the largest pulses. The integration times t_S and t_L were determined by optimising a figure of merit (FoM), which is a widely used measure of PSD ability.

Using the optimised integration times, an L - S spectrum was determined, shown in Figure 3.12. Shown are the two cuts made to separate neutrons from gamma rays. First, the dashed red line was drawn using `matplotlib.pyplot` in Python. The line was drawn to be close to the gamma ray locus (larger S) in order to include as many neutron events as possible. The solid blue line cuts out all events with L less than $0.25 \text{ MeV}_{\text{ee}}$. This value was chosen as it is the largest value of L for which the two loci could be effectively distinguished. Figure 3.13 shows the neutron light output spectrum after the cuts had been applied.

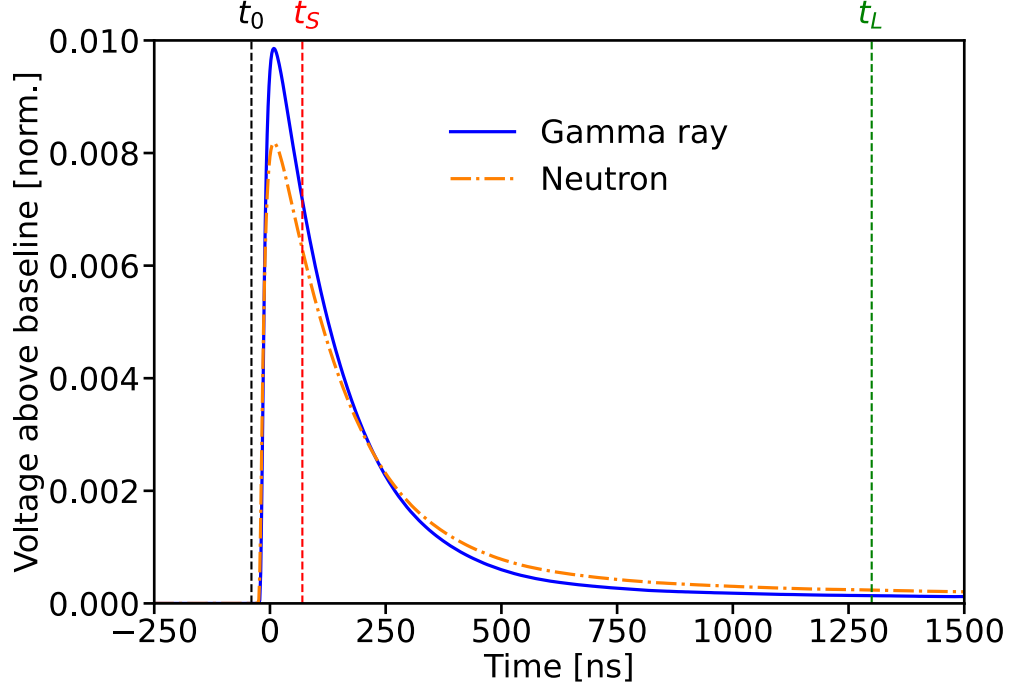


Figure 3.11: Typical event pulses from a $\varnothing$ 25 mm sphere of EJ-276 coupled to a SiPM, for gamma ray- and neutron-induced events. The integration times are shown, relative to the CFD-determined reference point t_{CFD} . Pulses have been normalised to the same long integral value.

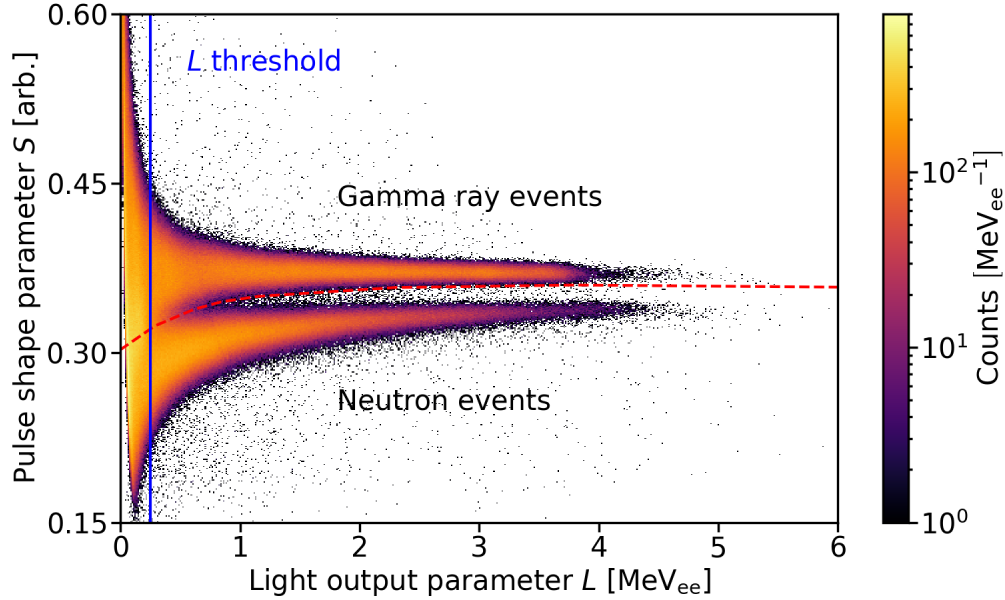


Figure 3.12: Events as a function of L and S for gamma rays and neutrons produced by the AmBe source at the n-lab, measured by a $\varnothing$ 25 mm sphere of EJ-276 coupled to a SiPM. Shown is the cut made to separate neutron and gamma ray events (red dashed) and the L threshold below which neutron and gamma ray events cannot be separated (blue solid).

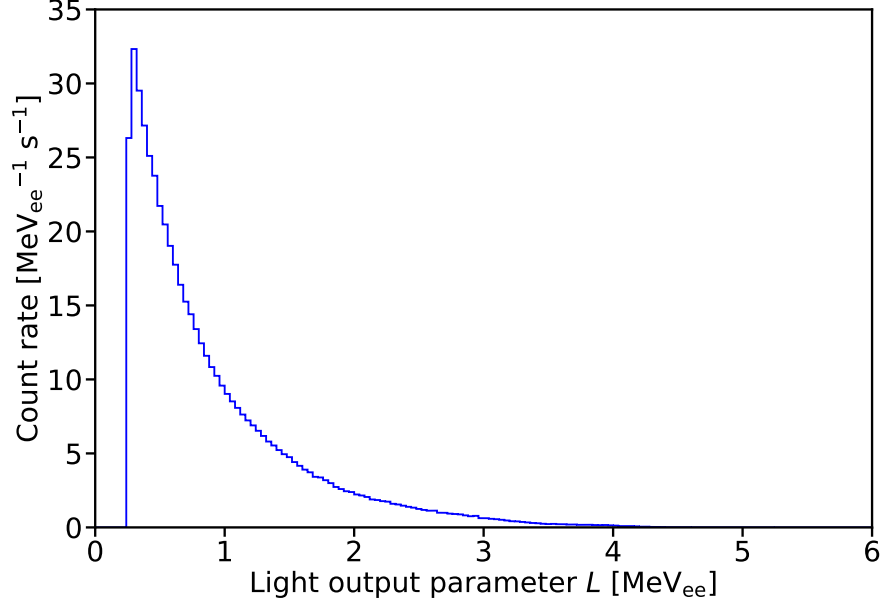


Figure 3.13: Light output spectrum of events corresponding to neutrons from the AmBe source at the n-lab, measured by a $\varnothing$ 25 mm sphere of EJ-276 coupled to a SiPM. Neutrons were separated from gamma rays using the cuts in Figure 3.12.

Figure of merit optimisation

For a given L - S spectrum, a slice of events between two L values is selected and then histogrammed according to S , as shown in Figure 3.14. The distance between the centroids of the two distributions (μ_1 , μ_2), divided by the sum of the widths of the distributions (FWHM₁, FWHM₂), is defined as the FoM [50]:

$$\text{FoM} = \frac{|\mu_1 - \mu_2|}{\text{FWHM}_1 + \text{FWHM}_2}. \quad (3.2)$$

The FoM was optimised first for a fixed t_L of 2000 ns, varying t_S . The t_L that is used to begin with is an arbitrary choice provided it's sufficiently long, so in this work a value found in previous studies was used [16]. Once t_S was determined to be 70 ns, it was fixed at that value and t_L was varied, repeating the process and settling on 1300 ns. A discrete set of integration times were tested, as shown in Figure 3.15, and the time with the maximum FoM was chosen to be optimal.

For the second optimisation, the change in t_L meant that the light output calibration was necessarily changing, so it was performed for each value of t_L that was tested. Once the optimal integration times were determined, they were fixed for all measurements made with the detector system.

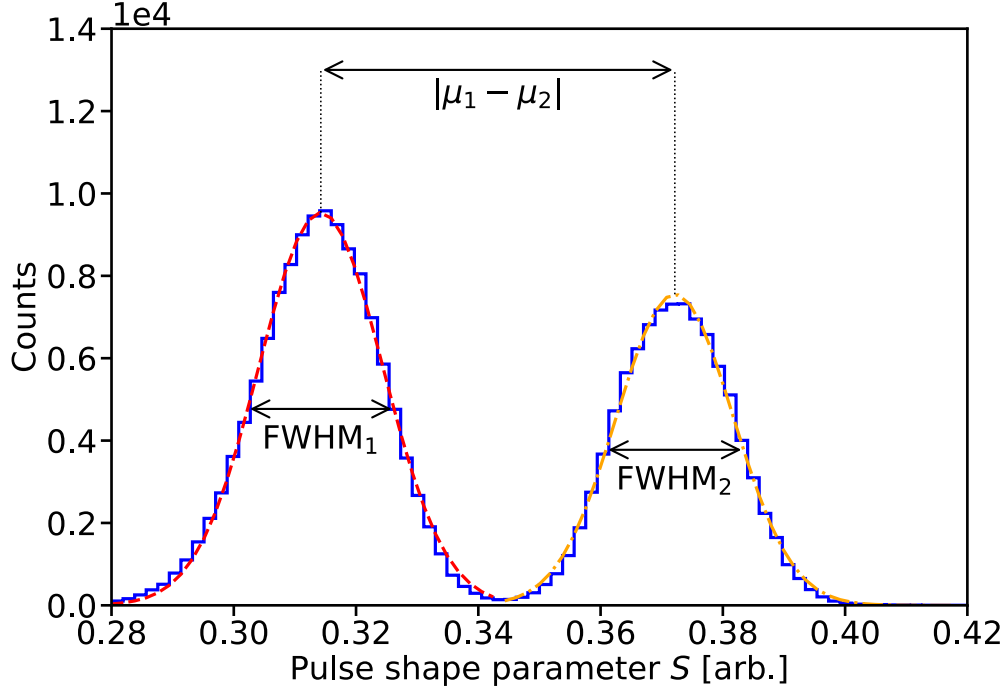


Figure 3.14: Example of a figure of merit calculation for $t_S = 70$ ns from measurements of an AmBe source at the n-lab, made with a $\varnothing$ 25 mm sphere of EJ-276 coupled to a SiPM. Events included are those with $0.8 \text{ MeV}_{ee} < L < 1.2 \text{ MeV}_{ee}$.

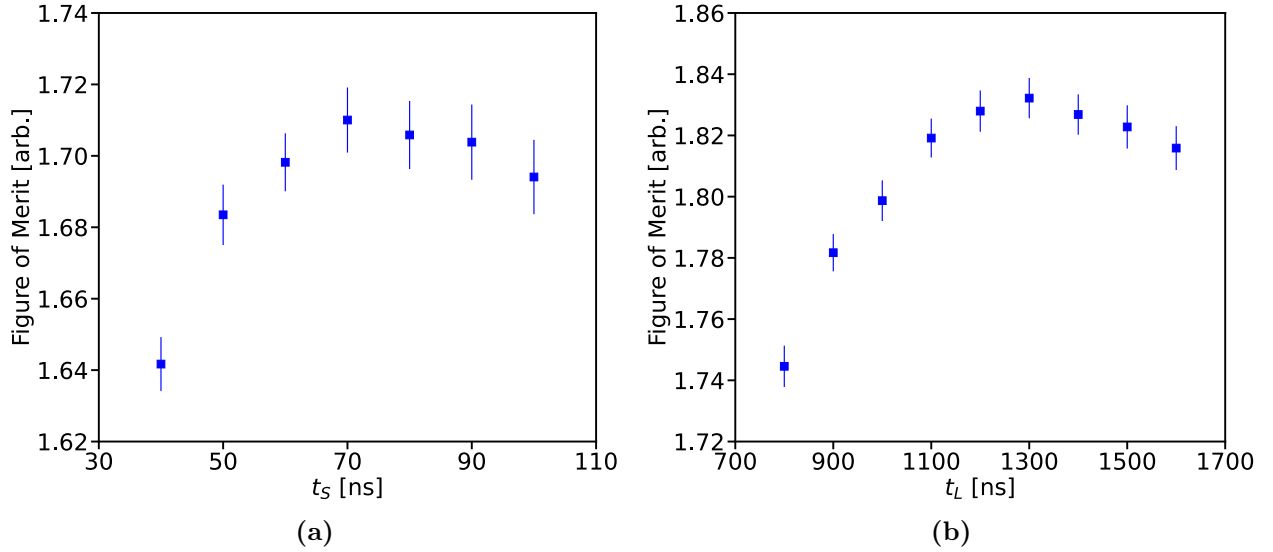


Figure 3.15: Figure of merit as a function of (a) t_S with $t_L = 2000$ ns and (b) t_L with $t_S = 70$ ns, as determined in (a). Optimal times were taken to be those with the largest figure of merit. Events included are those with $0.8 \text{ MeV}_{ee} < L < 1.2 \text{ MeV}_{ee}$.

3.4 Assessment of direction sensitivity

An important feature of the spherical detector system is its insensitivity to the direction of incident radiation. To test this, the response of the detector to 14.1 MeV neutrons produced by the STNG at the n-lab was analysed for a range of incident angles. The $\varnothing$ 25 mm sphere of EJ-276 coupled to a SiPM was mounted on a rotating table such that the centre of the scintillator was aligned with the axis of rotation, as shown in Figure 3.16(a). The beam of neutrons was collimated to a circular beam by a 1.0 m long HDPE collimator with an exit diameter of 26.6 mm and the detector placed such that the centre of the scintillator was 3076.0(8) mm from the neutron source. With this collimator insert, the beam at the position of the detector was wider than the detector, so the entire detector volume was irradiated by neutrons.

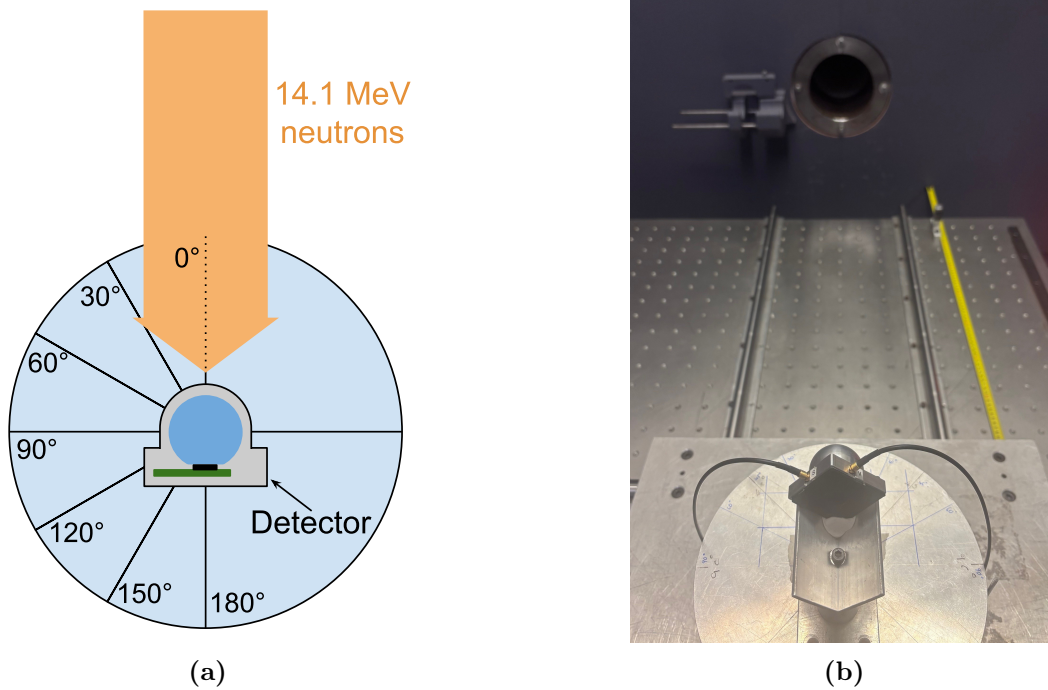


Figure 3.16: Experimental geometry for testing the response to neutrons incident on the detector from different angles. The $\varnothing$ 25 mm sphere of EJ-276 coupled to a SiPM is mounted on a rotating table facing the beam of neutrons, which are collimated to a circular beam with exit diameter 26.6 mm. To change the angle of incidence, the table was rotated to align the neutrons with the corresponding angle on the table. A diagram of the geometry (a) and the detector in position (b) are shown.

Measurements were made at 30° increments between 0° and 180°, for about 10 minutes per angle. Light output was calibrated to MeV_{ee} using ^{137}Cs and ^{22}Na as gamma ray sources, and the pulse shape parameter determined to produce *L-S* spectra, a subset of which are shown in Figure 3.17. Very little difference can be seen between the spectra.

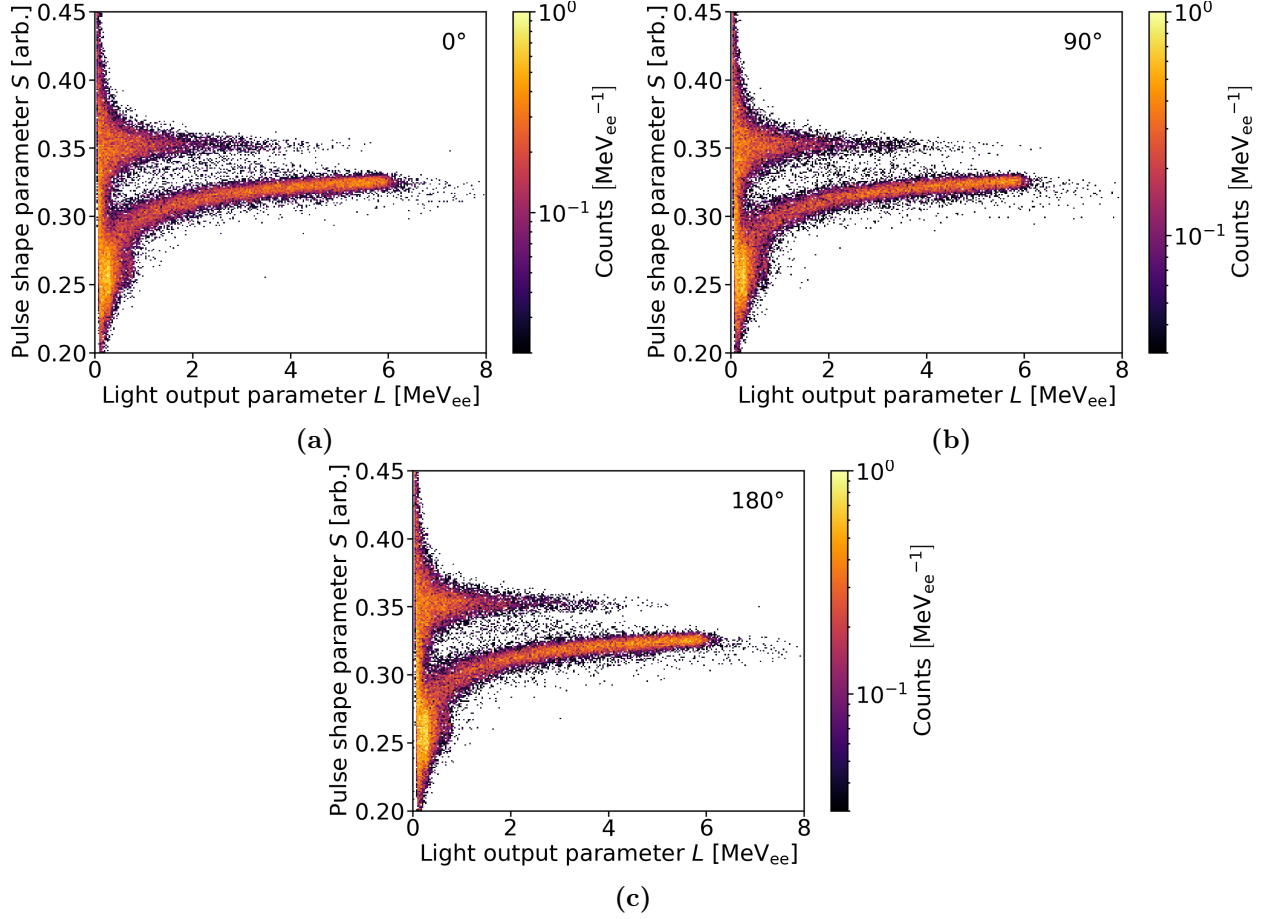


Figure 3.17: Events as a function of L and S for 14.1 MeV neutrons produced by the STNG at the n-lab and the induced gamma ray background, measured by a $\varnothing$ 25 mm sphere of EJ-276 coupled to a SiPM. Measurements made with incident neutron angles of (a) 0° , (b) 90° , and (c) 180° . Counts are normalised to unit maximum bin intensity.

Neutron and gamma ray events were separated using PSD cuts and neutron light output spectra determined, a subset of which are shown in Figure 3.18, with the spectra normalised to unit integral. Since there is no discernable difference in the spectra in terms of energy resolution and edge position, more rigorous tests were performed.

The edge position for each spectrum was determined by taking the gradient of the light output histogram and fitting a Gaussian function to the result, taking the centroid value as the edge position. Figure 3.19 shows the edge position for each angle as a percentage relative to the edge position at 0° . The edge positions and their uncertainties are all within 1% of the 0° edge. The requirements determined for this work were a deviation of light output response less than 20% over all angles, so the spherical detector is well within those requirements.

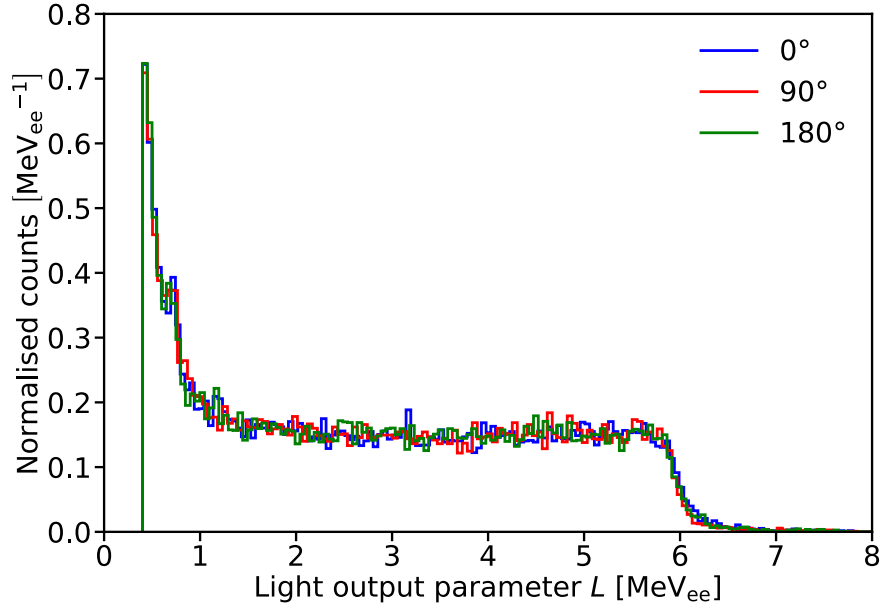


Figure 3.18: Neutron light output spectra for the 14.1 MeV STNG neutron source in the n-lab, measured by a $\varnothing$ 25 mm sphere of EJ-276 coupled to a SiPM at incident angles of 0° , 90° , and 180° . Spectra are normalised to unit area.

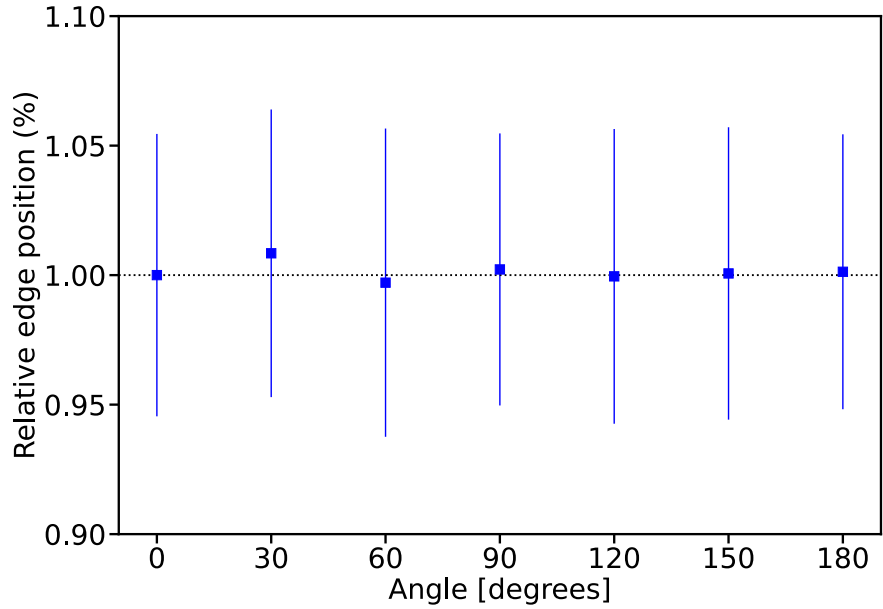


Figure 3.19: Edge position of the neutron light output spectra for 14.1 MeV neutrons measured with a $\varnothing$ 25 mm sphere of EJ-276 coupled to a SiPM as a function of the incident angle of neutron beam. Edge positions are represented as a percentage of the position (in MeV_{ee} units) relative to the 0° measurement.

The measurement time was recorded for each measurement and the neutron count rate determined for each angle, shown in Figure 3.20 as a percentage relative to the count rate at 0° , and are seen to be consistent with each other within two standard uncertainties. The spherical detector system shows at most 6% deviation in response when the angle of incident radiation is changed, so the detector is determined to be insensitive to the direction of incident radiation.

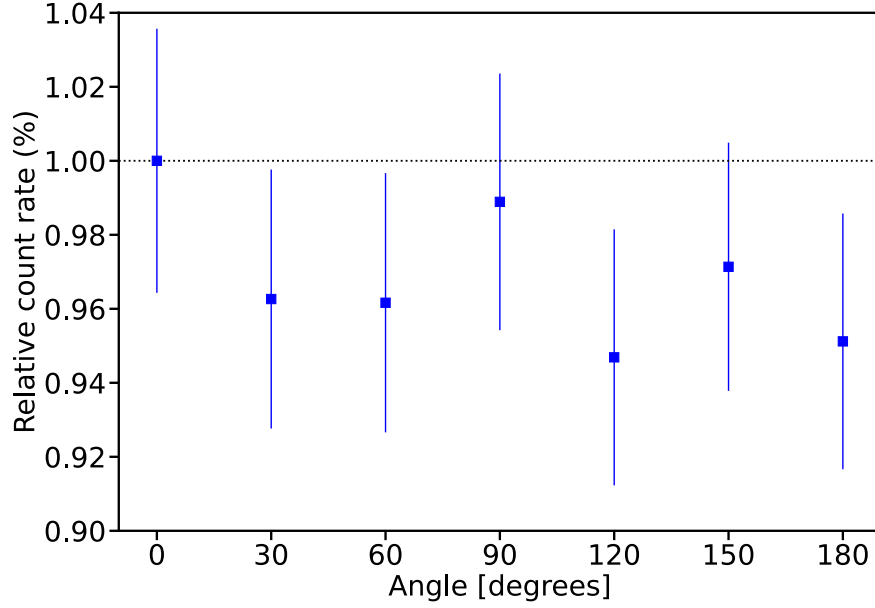


Figure 3.20: Neutron count rate for 14.1 MeV neutrons measured with a $\varnothing$ 25 mm sphere of EJ-276 coupled to a SiPM as a function of the incident angle of neutron beam. Count rate is represented as a percentage of the rate relative to the 0° measurement. Uncertainties are displayed as two standard deviations.

Chapter 4

Measurements at fast neutron metrology facilities

In order to characterise the detector system as a neutron spectrometer, measurements were made at two fast neutron metrology facilities. The Accelerator for Metrology and Neutron Applications in External Dosimetry (AMANDE) facility at the Institut de Radioprotection et de Sûreté Nucléaire (IRSN) facility in Cadarache, France, can produce monoenergetic neutron beams between 2 keV and 20 MeV. The Physikalisch Technische Bundesanstalt (PTB) in Braunschweig, Germany has their PTB Ion Accelerator Facility (PIAF), which houses a cyclotron that can produce broad spectrum neutrons with energy measured using the time-of-flight technique. Measurements of these fields were used to produce detector response functions for use in unfolding. The Tandetron at PTB was also used to produce monoenergetic neutron beams.

4.1 AMANDE

The AMANDE facility at IRSN Cadarache in France is a fast neutron metrology facility that provides monoenergetic peak energy neutron fields between 2 keV and 20 MeV. A 2 MV HVEE Tandetron accelerates protons or deuteron ions onto deuterium or tritium targets (embedded in titanium), which undergo fusion reactions to produce neutrons where the energy of the neutrons depends on the energy of the incident ion, the type of both target and ion, and the angle that the neutron is ejected at relative to the ion beam. By varying these parameters, the peak neutron energy can be selected. The facility features a $\varnothing 5\text{ cm} \times 5\text{ cm}$ cylindrical BC-501A organic liquid scintillator coupled to a 12-stage PMT as a reference detector as well as long counters that are used to scale the detector response to fluence [19]. Measurements were made with the reference detector to provide fluence values for the measurements made with the $\varnothing 25\text{ mm}$ sphere of EJ-276 on a SiPM.

The measurement hall at AMANDE, shown in Figure 4.1, was designed to minimise backscattered neutrons from the structural components. It contains the ion delivery beam, the interchangeable target on a rotating mount, and two movable arms upon which

detectors can be mounted. The arms can swing between -160° and $+160^\circ$ relative to the ion beam and the mounting points can move along rails to place the detectors anywhere between 0.5 m and 6.0 m from the target.



Figure 4.1: The AMANDE experiment hall. Coming from the right is the beamline, which is incident on the target at the centre. Movable arms allow for the placement of detectors anywhere between -160° and $+160^\circ$ to the ion beam, and between 0.5 m and 6.0 m from the target.

The spherical detector system was placed on one of the movable arms with the front face of the detector 1003(1) mm from the target, making the centre of the scintillator 1021(1) mm from the target, shown in Figure 4.2. Light output spectra corresponding to 4 peak neutron energies were measured, summarised in Table 4.1. Measurements were made for about 7 minutes at each energy, aiming for around 6×10^5 events in the detector to ensure the light output spectra have enough events to be statistically significant.

Light output was calibrated to the MeV_{ee} scale using only a ^{137}Cs gamma ray source, so instead of using a linear fit, the single Compton edge energy was used to calibrate, assuming a y -intercept of 0. This method is considered acceptable when there is no alternative, but it can underestimate the light output slightly. This can be seen in Figure 3.9 as the y -intercept using multiple calibration points is less than zero, so the gradient will be slightly higher than if only one point was used.

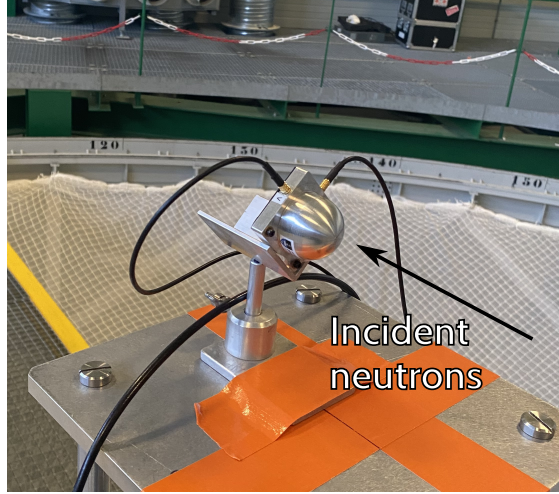


Figure 4.2: The detector, made of a $\varnothing$ 25 mm sphere of EJ-276 coupled to a SiPM, in position on one of the movable arms in the AMANDE experiment hall, with the front face of the detector 1003(1) mm from the target.

Table 4.1: Neutron fields measured at AMANDE. Measurement angle θ refers to the angle the detector was positioned at with respect to the ion beam. Energies and their uncertainty from [19].

Beam	Reaction	Target	Target thickness	θ	Peak neutron energy at θ
d @ 432 keV	${}^3\text{H}(\text{d},\text{n}){}^4\text{He}$	TiT	$200 \mu\text{g cm}^{-2}$	90°	14.1(2) MeV
d @ 1840 keV	${}^2\text{H}(\text{d},\text{n}){}^3\text{He}$	TiD	$200 \mu\text{g cm}^{-2}$	0°	5.00(3) MeV
p @ 3310 keV	${}^3\text{H}(\text{p},\text{n}){}^3\text{He}$	TiT	$200 \mu\text{g cm}^{-2}$	0°	2.50(2) MeV
p @ 2037 keV	${}^3\text{H}(\text{p},\text{n}){}^3\text{He}$	TiT	$120 \mu\text{g cm}^{-2}$	0°	1.20(2) MeV

Shown in Figure 4.3 are the L - S spectra associated with each measurement, along with the cuts used to separate neutron and gamma ray events. The resulting neutron light output spectra are shown in Figure 4.4.

Measurements were made of the 14.1(2) MeV and 5.00(3) MeV fields using a detector composed of a $\varnothing$ 25 mm $\times$ 25 mm cylinder of EJ-276 mounted on a $\varnothing$ 25 mm Scionix 1M-E1-X photomultiplier tube, in the interest of comparing the spherical, SiPM-based detector to something of a more traditional shape and construction. The light output edge resolution and PSD ability were compared (Appendix A) and the SiPM-based detector was found to be an improvement in both respects.

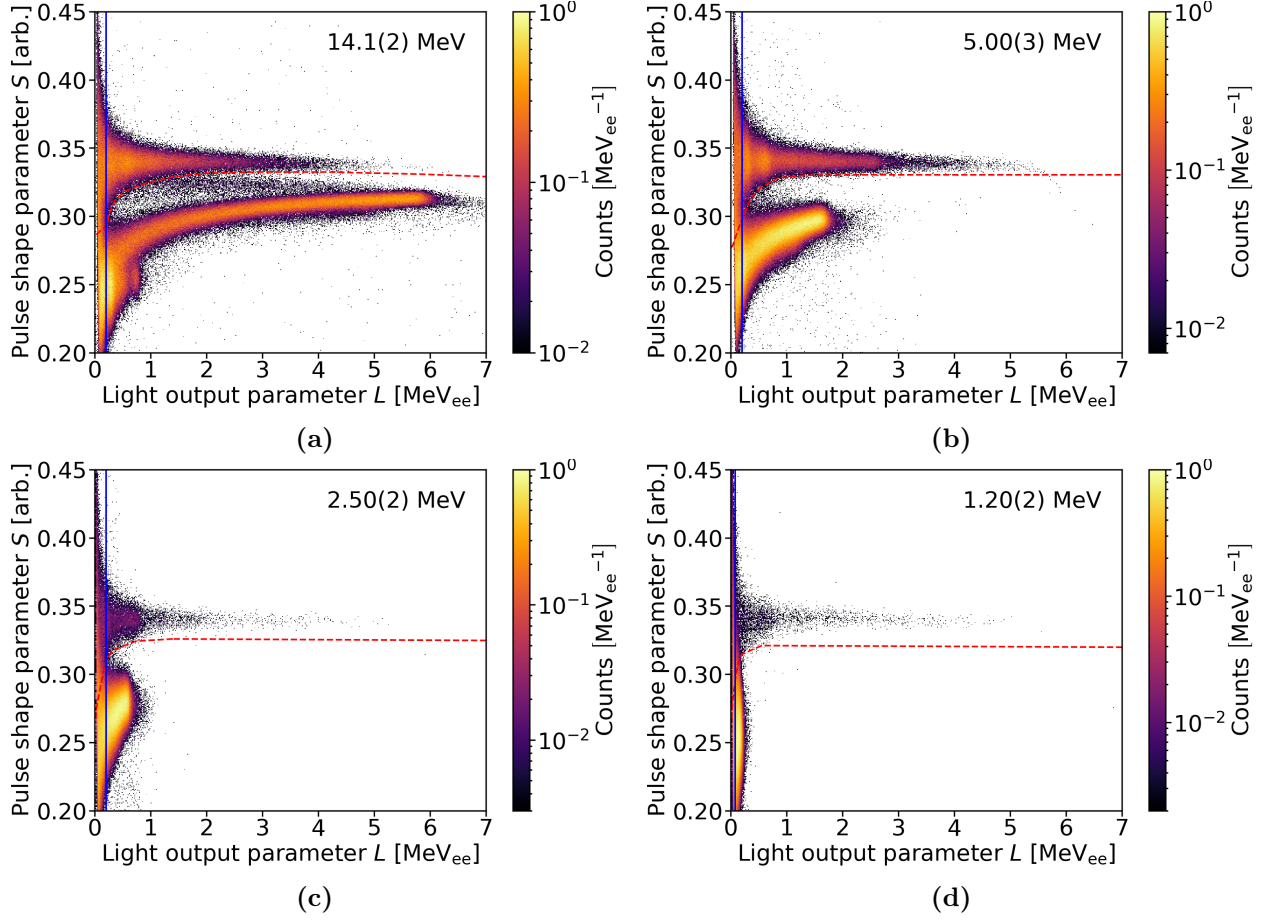


Figure 4.3: Events as a function of L and S for gamma rays and neutrons produced using ion beams incident on targets, with the parameters specified in Table 4.1, measured by a $\varnothing$ 25 mm sphere of EJ-276 coupled to a SiPM at the AMANDE facility. Peak neutron energies were (a) 14.1(2) MeV, (b) 5.00(3) MeV, (c) 2.50(2) MeV, and (d) 1.20(2) MeV. PSD cuts are shown in red (dashed) and L threshold cuts are shown in blue (solid). Neutron events are below the PSD cut and gamma ray events are above. Counts are normalised to unit maximum bin intensity.

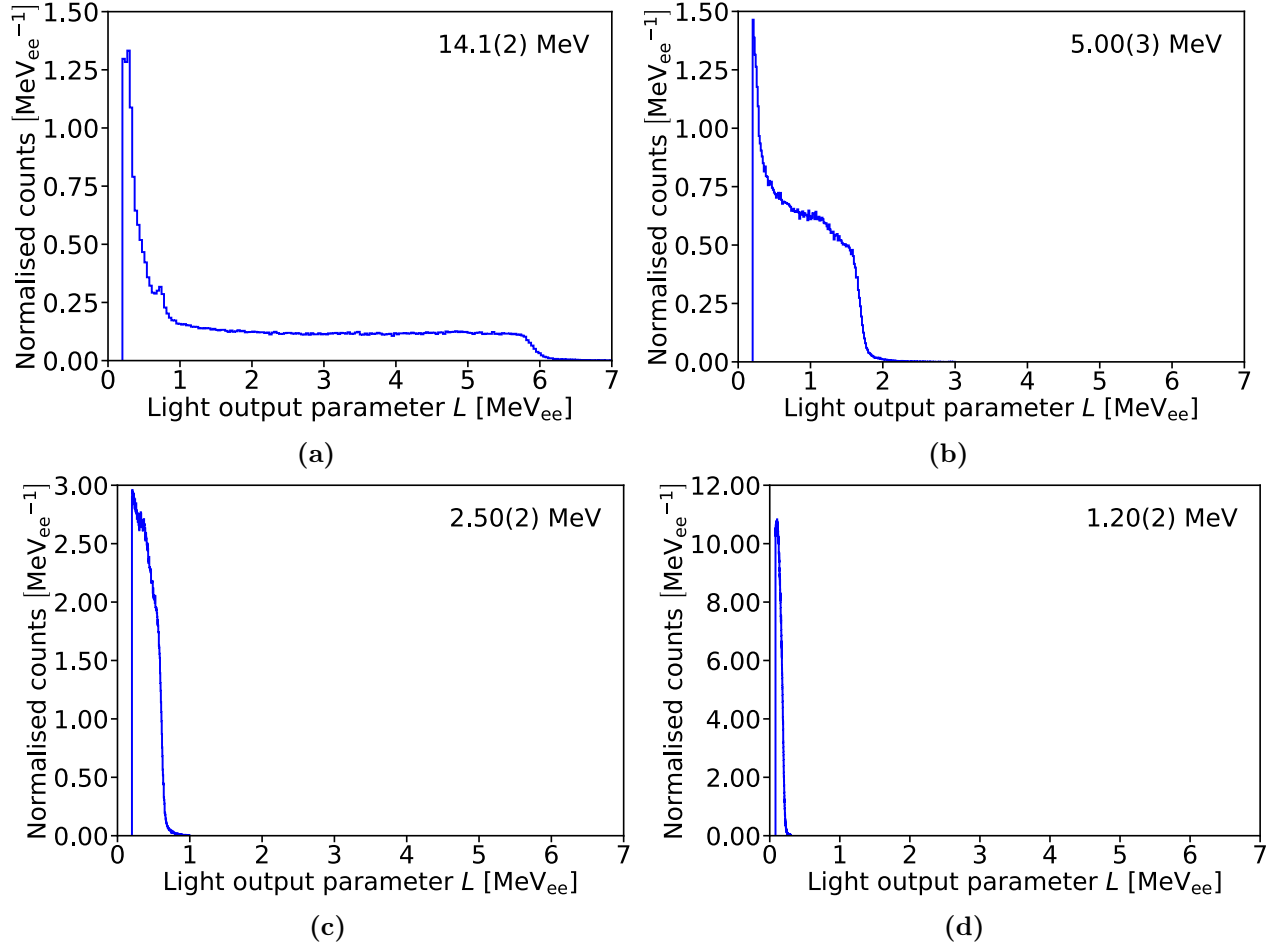


Figure 4.4: Neutron light output spectra measured by a $\varnothing$ 25 mm sphere of EJ-276 coupled to a SiPM for neutron fields with peak energy (a) 14.1(2) MeV, (b) 5.00(3) MeV, (c) 2.50(2) MeV, and (d) 1.20(2) MeV at the AMANDE facility. Spectra are normalised to unit integral.

4.2 PIAF

The PIAF at the Physikalisch Technische Bundesanstalt in Braunschweig, Germany, has a neutron metrology facility that houses a 2 MV Tandetron and a CV28 cyclotron, both of which can accelerate proton, deuteron, and alpha beams for direct use or to generate secondary fields such as broad spectrum or monoenergetic neutrons. The beams can be operated in pulsed mode with ns time resolution to allow for time-of-flight measurements.

4.2.1 Broad spectrum neutron fields with time-of-flight

The CV28 cyclotron was used to produce neutrons with a broad energy spectrum, using time-of-flight to measure the energy of neutrons incident on the detector [51]. Figure 4.5 shows a schematic of the cyclotron system, with 5 places where detectors can be secured. The reference detector for the cyclotron system is a $\varnothing 5\text{ cm} \times 2.5\text{ cm}$ cylindrical BC-501A organic liquid scintillator coupled to a PMT. The reference detector was fixed in place at position D5 and measurements were made of the neutron energy spectrum. The fluence was also reconstructed from this measurement. The cyclotron assembly was then rotated around the target such that position D3 was at the same angle relative to the ion beam as D5 was when the reference measurements were made.

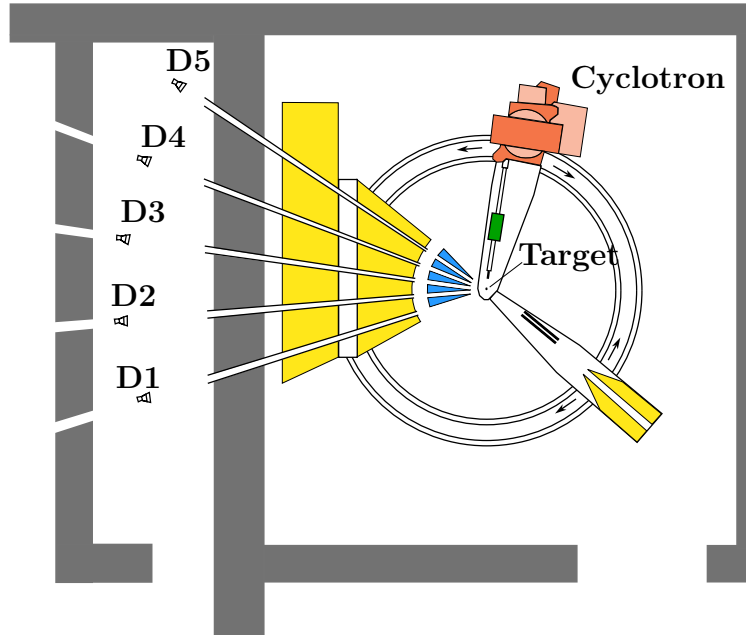


Figure 4.5: Schematic of the beam delivery system at PIAF [51]. The reference detector was placed at D5 and the measurements were made at D3. The cyclotron can be moved to place any of the detectors at the same angle relative to the ion beam.

Protons were accelerated by the cyclotron to an energy of $\sim 17\text{ MeV}$, irradiating a natural beryllium target that was sufficiently thick ($\sim 5\text{ mm}$) in order to stop a 20 MeV proton, which has a range of 2.8 mm in beryllium, producing a neutron field with energies up to

16 MeV. An incident proton can either undergo charge exchange immediately, producing a neutron, or it can scatter and lose some energy before interacting again, which results in a broadened spectrum of emitted neutron energies.

The spherical EJ-276 detector was placed such that its front face was 11.998(1) m from the beryllium target, shown in Figure 4.6. The beam profile was wide enough to irradiate the entire detector volume. The required +28.5 V bias was supplied by a CAEN N1419 4-channel NIM HV power supply module, patched between the data room and experimental vault via long coaxial cables. The detector signal was patched back through similar cables to the digitiser. The RF pulse from the time-of-flight system was also patched to the digitiser. The field was measured for 10 hours with a beam current of 240 nA, recording around 3.1×10^7 events.

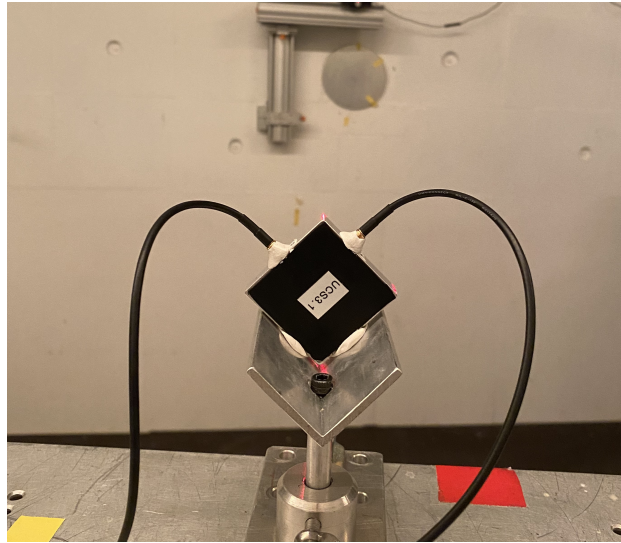


Figure 4.6: The detector in position D3 of the cyclotron at PIAF. Gamma rays and neutrons were incident through a collimator in the wall, which was covered when the picture was taken (grey circle).

The time-of-flight technique was used to measure the energy of the incident neutron associated with a given event in the detector. The beam was operated in ns-pulsed mode, providing a proton and an associated RF pulse sent to the digitiser at a frequency of 959.60(3) kHz. Channel 0 of the digitiser recorded the signal from the detector and channel 1 recorded the signal from the RF system. When a detector event signal crossed a pre-defined voltage threshold, the digitiser recorded 3000 ns on channels 0 and 1, capturing a pre-trigger region of 400 ns. Figure 4.7 shows a typical event trace along with the RF pulse captured at the same time.

In order to find the time difference between a neutron being produced in the target and detected in the detector, the time difference between the detected event and the next RF pulse was found. This was labelled as T_{diff} as shown in Figure 4.7. The last RF pulse in the window was used as it is guaranteed to always come after the event pulse, which simplifies the analysis. The time t_{CFD} was used as the reference point for the event pulse,

using the same CFD technique as that discussed in Section 3.3.2. The same process was applied to the RF pulse to determine a reference point. When calculating the pulse integrals, t_{CFD} was chosen to be the sample before the CFD pulse crossed the baseline, however since ToF requires finding the difference between the reference times, this would result in a discretisation of T_{diff} according to the sample width of the digitiser (2 ns).

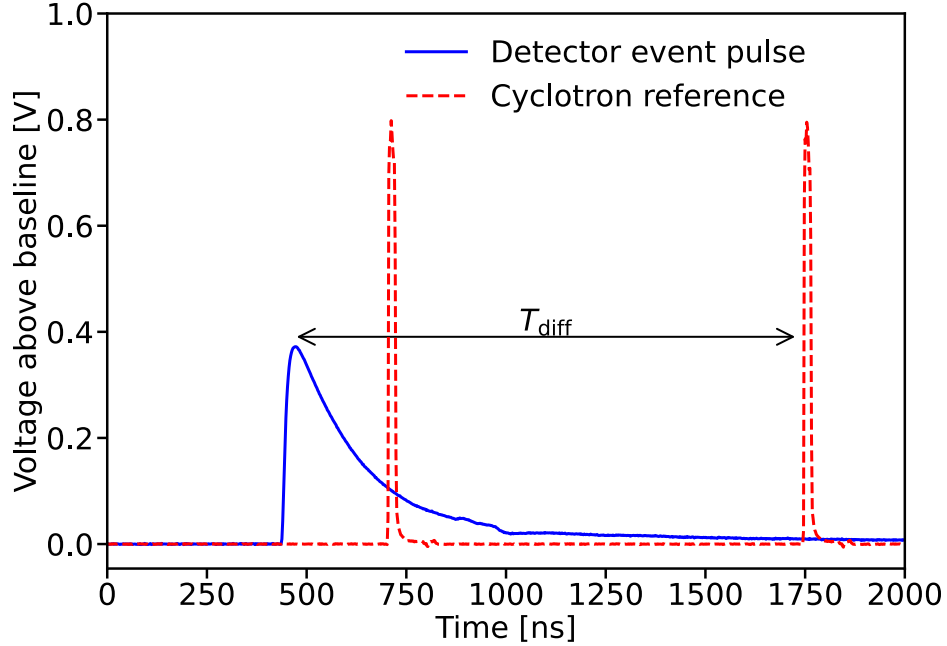


Figure 4.7: An example event from the measurement of neutrons with energy < 16 MeV using a $\varnothing$ 25 mm sphere of EJ-276 coupled to a SiPM. Two cyclotron RF pulses are shown together with the time difference T_{diff} used in the time-of-flight analysis.

A linear interpolation was used to find the time at which the pulse crossed the baseline, using two samples on either side of the crossing. In this way, T_{diff} was determined for each event, shown in Figure 4.8. Note that events with a larger T_{diff} arrive at the detector earlier, with respect to the time at which an interaction occurs in the target. The sharp peak around 1550 ns is the primary gamma ray peak, as gamma rays are expected to all arrive at the detector at the same time relative to being created in the reaction at the target. To the left of the gamma ray “flash” is the main neutron locus, where there is a spreading of arrival times as neutrons with different kinetic energies travel at different speeds. The two peaks around 600 ns are gamma rays associated with issues with the pulse selector system in the cyclotron.

Examining the region around the gamma ray flash reveals the peak shown in Figure 4.9. The peak is not symmetric: protons incident on the beryllium target either undergo a reaction with the beryllium immediately, resulting in either a gamma ray, a neutron, or both; or they scatter elastically and then react at some later time. Those immediate reactions will result in gamma rays that are all emitted at the same time, thus they will show up as a symmetric Gaussian in the gamma ray flash. The other events, however, are slightly time-delayed so they result in the slight smearing of the distribution towards lower T_{diff} .

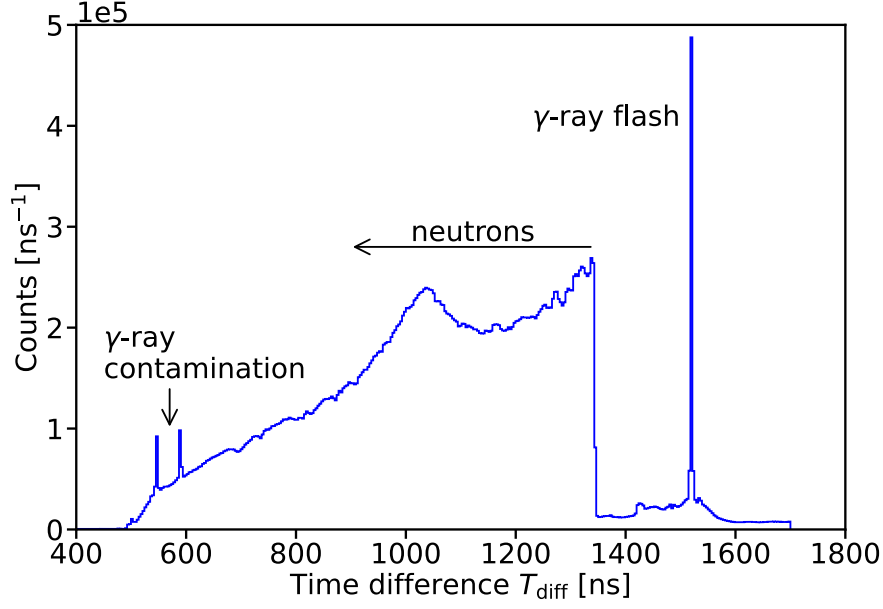


Figure 4.8: Time difference T_{diff} between the event pulse and the cyclotron RF pulse for gamma rays and neutrons produced by 17 MeV protons irradiating a thick beryllium target, measured at a target-detector distance of 12.016(1) m.

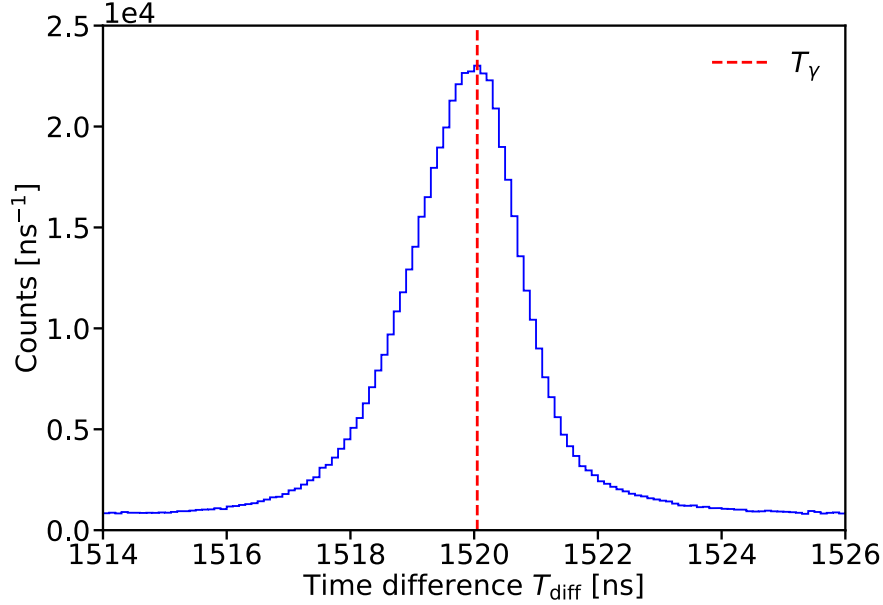


Figure 4.9: A small region of the uncalibrated time difference T_{diff} , showing the distribution of gamma rays produced by 17 MeV protons irradiating a thick beryllium target, measured at a target-detector distance of 12.016(1) m.

The position of the peak was chosen to be at the centre of the most intense bin, which is $T_\gamma = 1520.05(5)$ ns. The uncertainty on this measurement was chosen to be the edges of the bin. The distance from target to detector face was measured as 11.998(1) m. However,

neutrons and gamma rays could interact at any position in the active volume. As this position cannot be known on an event-by-event basis, the position considered for time-of-flight was chosen to be at the centre of the scintillator. The corrected distance was then $d = 12.016(1)$ m, so the time taken for a gamma ray to reach the detector was $d/c = 40.082(1)$ ns, which was used to determine the calibrated time-of-flight parameter T as

$$T = -(T_{\text{diff}} - T_{\gamma}) + \left(\frac{d}{c}\right). \quad (4.1)$$

This was calculated for each event, resulting in the time-of-flight spectrum shown in Figure 4.10.

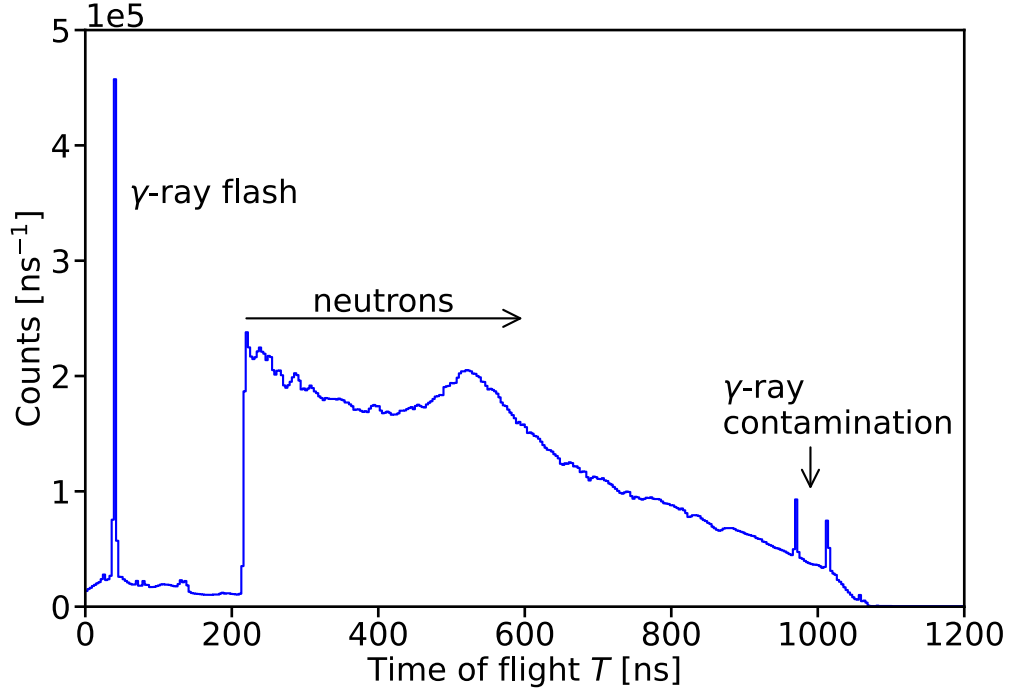


Figure 4.10: Time of flight parameter T for gamma rays and neutrons produced by 17 MeV protons irradiating a thick beryllium target, measured at a target-detector distance of 12.016(1) m using a $\varnothing$ 25 mm sphere of EJ-276 coupled to a SiPM, calibrated using the gamma ray flash.

Neutron events were separated from gamma ray events using PSD. Figure 4.11 shows the L - S spectrum as well as the cuts used to select neutron events. The neutron cut was placed close to the gamma ray locus and the L threshold of $0.25 \text{ MeV}_{\text{ee}}$ was chosen as it is the largest value of L for which the two loci could be effectively distinguished. Figure 4.12 shows the T spectrum after the PSD and L threshold cuts were applied.

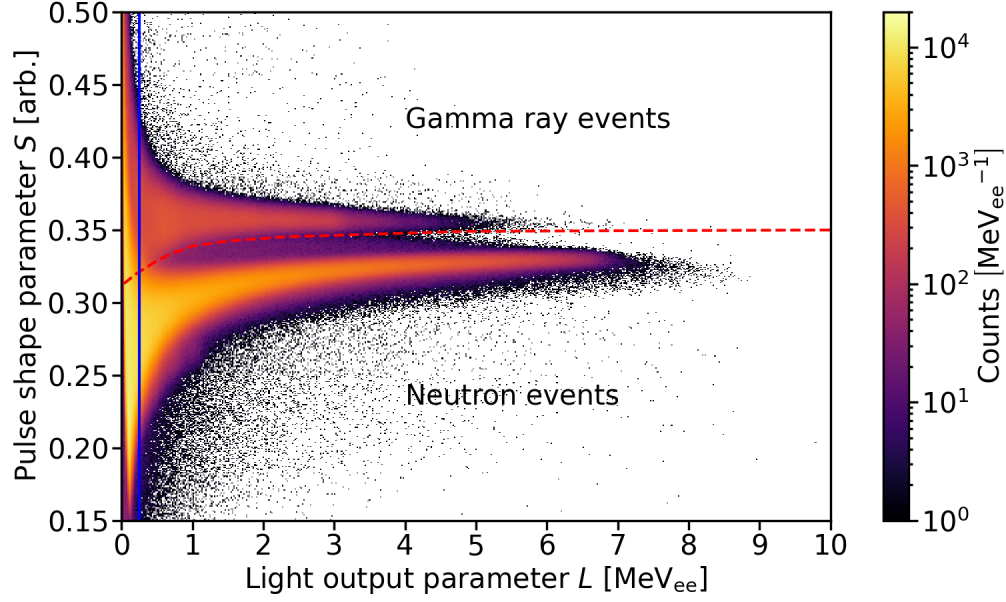


Figure 4.11: Events as a function of L and S for gamma rays and neutrons produced by 17 MeV protons irradiating a thick beryllium target, measured at a target-detector distance of 12.016(1) m using a $\varnothing$ 25 mm sphere of EJ-276 coupled to a SiPM. Shown is the cut made to separate neutron and gamma ray events (red dashed) and the L threshold below which neutron and gamma ray events cannot be separated (blue solid).

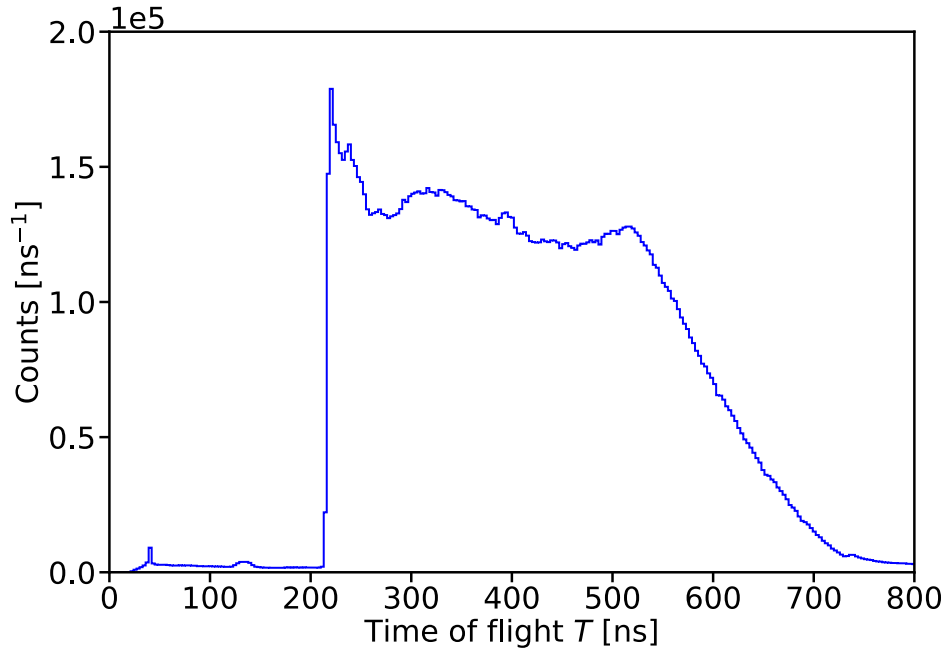


Figure 4.12: Time of flight parameter T for neutrons produced by 17 MeV protons irradiating a thick beryllium target, measured at a target-detector distance of 12.016(1) m using a $\varnothing$ 25 mm sphere of EJ-276 coupled to a SiPM. Neutron events were separated from gamma ray events using PSD and with an L threshold of 0.25 MeV_{ee}.

The energy of each incident neutron was determined from

$$E_n = m_n c^2 \left(\frac{1}{\sqrt{1 - \frac{d^2}{T^2 c^2}}} - 1 \right), \quad (4.2)$$

with $m_n = 939.565 \text{ MeV}/c^2$ and $d = 12.016(1) \text{ m}$. The result was histogrammed to produce the energy spectrum shown in Figure 4.13. To determine the incident spectral fluence, corrections need to be made for detector efficiency.

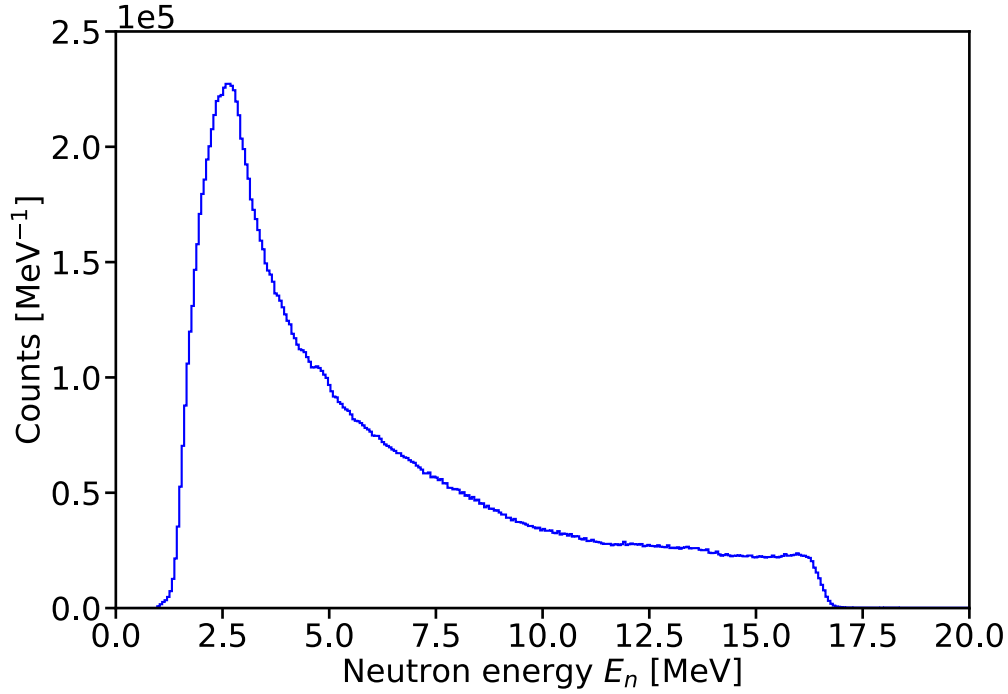


Figure 4.13: Incident neutron energy for each event in the detector, for neutrons produced by 17 MeV protons irradiating a thick beryllium target, measured at a target-detector distance of 12.016(1) m using a $\varnothing$ 25 mm sphere of EJ-276 coupled to a SiPM. Energy determined using the time-of-flight technique. Neutron events were separated from gamma ray events using PSD and with an L threshold of 0.25 MeV_{ee}.

Nearly monoenergetic neutron lineshapes were created from the broad spectrum measurement by taking slices of the light output spectrum with respect to the incident neutron energy as shown in Figure 4.14. Software cuts with smaller ranges in energy lead to better energy resolution, but too small of a cut results in a light output spectrum not having enough events to be statistically significant, so cuts of width 0.25 MeV were chosen to balance these effects.

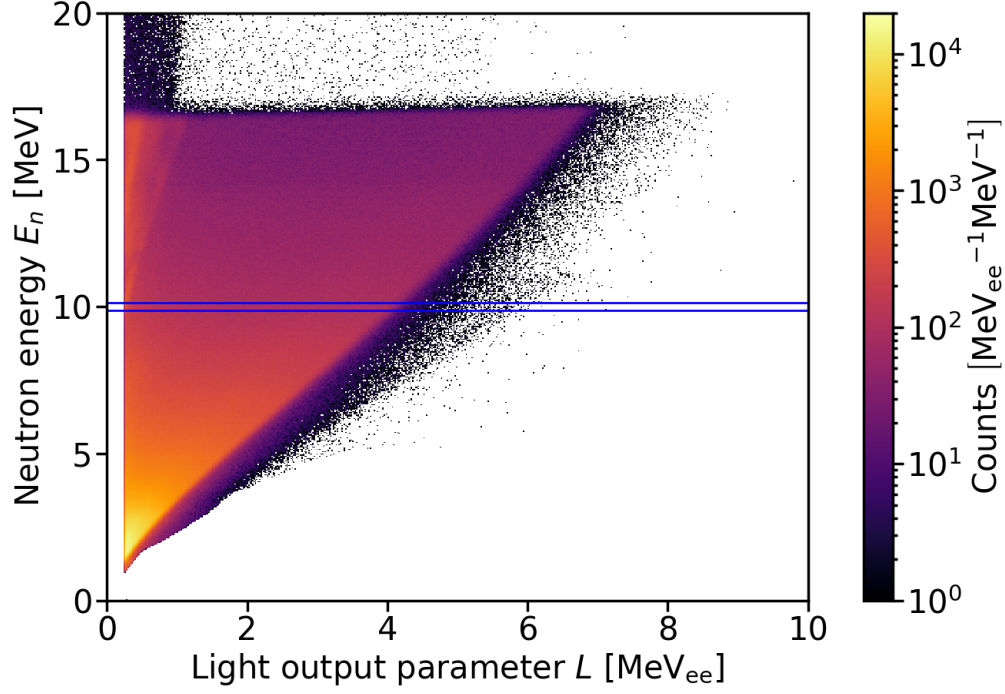


Figure 4.14: Events as a function of light output parameter L and neutron energy E for neutrons produced by 17 MeV protons irradiating a thick beryllium target, measured at a target-detector distance of 12.016(1) m using a $\varnothing$ 25 mm sphere of EJ-276 coupled to a SiPM. A cut in neutron energy of width 0.25 MeV and centred at 10 MeV is shown in blue as an example.

A subset of the lineshapes is shown in Figure 4.15. Each lineshape is a histogram of light output parameter L , with 250 bins and covering the 0–10 MeV_{ee} range. Lineshapes are labelled according to the energy at the centre of the bin. Due to the light output threshold of 0.25 MeV_{ee} as a result of the PSD process, the lineshapes are cut off below that L value.

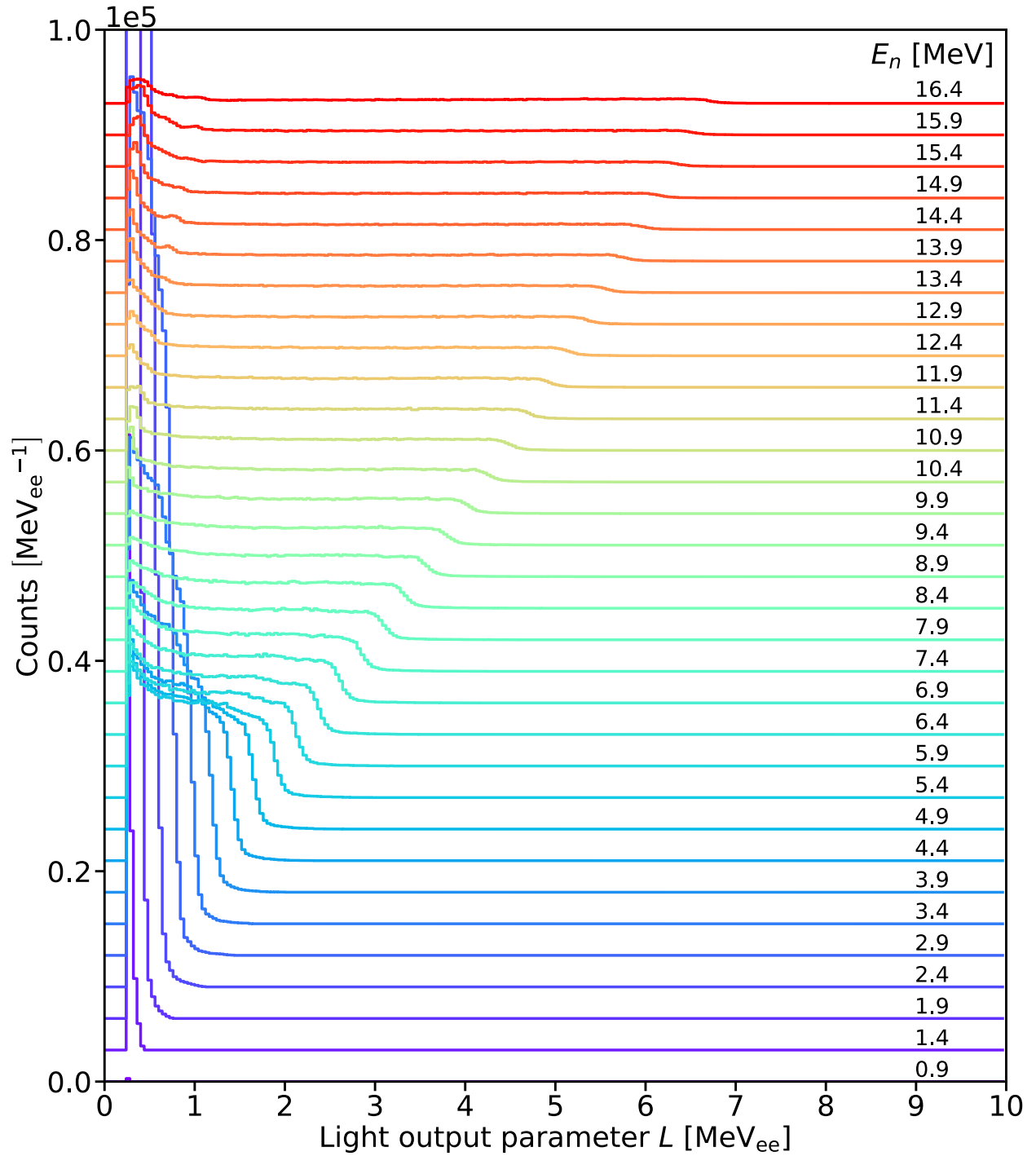


Figure 4.15: A subset of the neutron lineshapes for a $\varnothing$ 25 mm sphere of EJ-276 coupled to a SiPM, measured using the PIAF cyclotron. Protons of energy 17 MeV irradiated a thick beryllium target, producing broad spectrum neutrons up to 16 MeV. Energy was measured using the time-of-flight technique and neutrons separated into energy bins of width 0.25 MeV. Lineshapes have been shifted vertically for visualisation purposes.

4.2.2 Monoenergetic neutron fields

The measurement hall for the 2 MV Tandetron is shown in Figure 4.16, with the spherical EJ-276 detector in position. Detectors can be mounted on movable arms to change the distance and angle to the target. Two neutron fields were measured with the Tandetron, as laid out in Table 4.2. The 19.0(3) MeV field was contaminated with neutrons around 5.8 MeV, but the time-of-flight technique was used to determine the neutron energy and separate the high and lower energy neutrons.

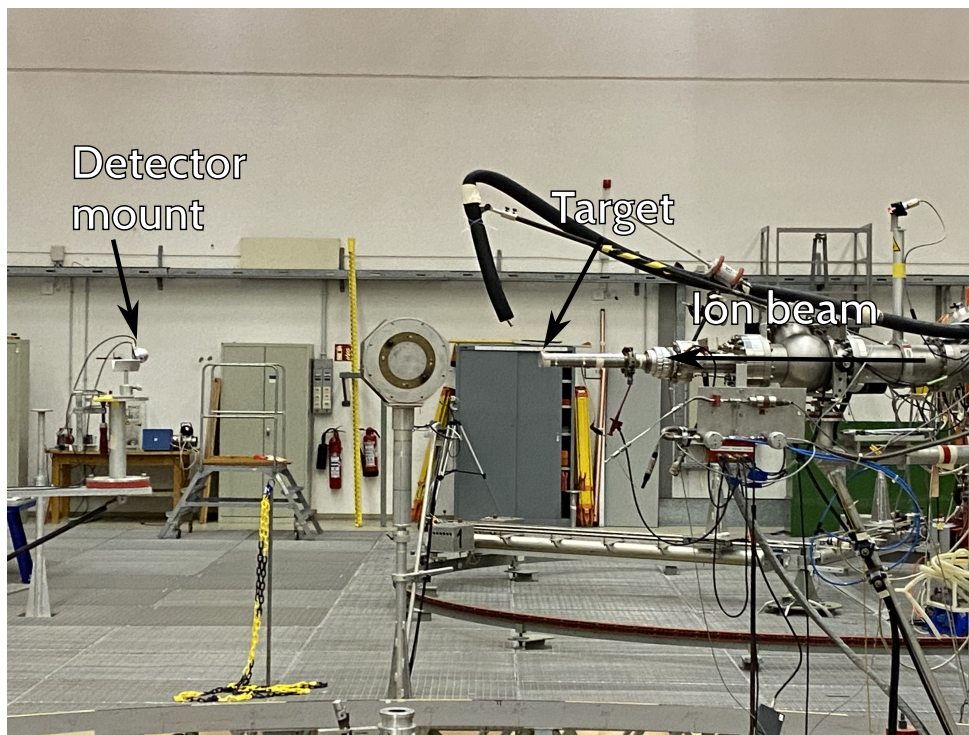


Figure 4.16: The measurement hall for the 2 MV Tandetron at PIAF [51]. The target rotates for even irradiation. Detectors are mounted on arms that can move to change the angle and distance relative to the target.

Table 4.2: Neutron energies measured at PIAF. Measurement angle refers to the angle with respect to the ion beam. Energies and their uncertainty from [52].

Beam	Reaction	Target	Target thickness	θ	Peak neutron energy at θ
d @ 2674 keV	$^3\text{H}(\text{d},\text{n})^4\text{He}$	TiT	$1000 \mu\text{g cm}^{-2}$	0°	19.0(3) MeV
d @ 215 keV	$^3\text{H}(\text{d},\text{n})^4\text{He}$	TiT	$1000 \mu\text{g cm}^{-2}$	0°	14.8(4) MeV

Light output spectra were measured for both peak neutron energies, recording for about 30 minutes to obtain a similar amount of detector events as were measured at IRSN AMANDE. Shown in Figure 4.17 are the L - S spectra associated with each measurement, along with the cuts used to separate neutron and gamma ray events. The resulting neutron light output spectra are shown in Figure 4.18

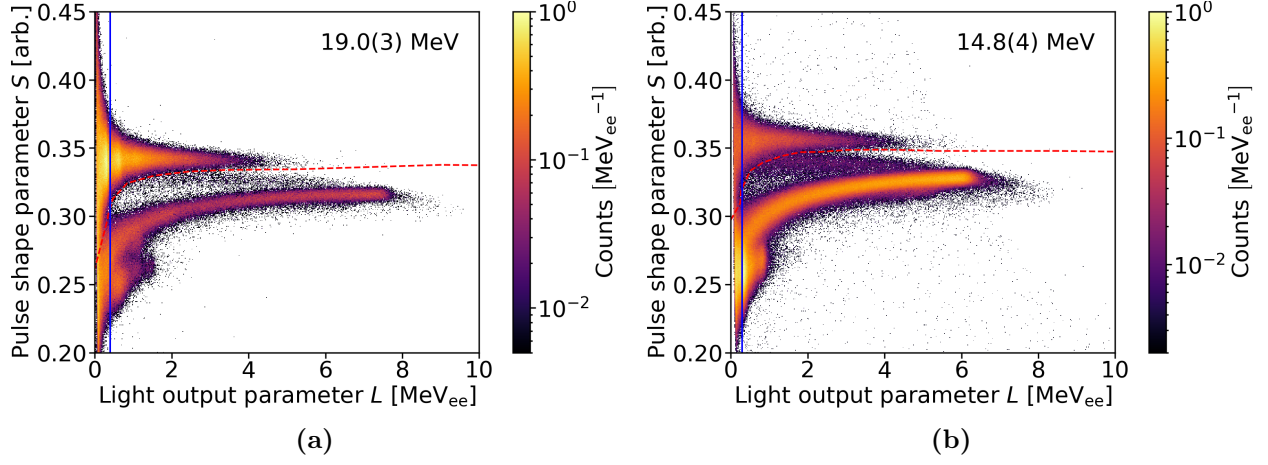


Figure 4.17: Events as a function of L and S for gamma rays and neutrons produced by the PIAF Tandetron, with the parameters specified in Table 4.2, measured by a $\varnothing$ 25 mm sphere of EJ-276 coupled to a SiPM. Peak neutron energies were (a) 19.0(3) MeV and (b) 14.8(4) MeV. The 19.0(3) MeV measurement was contaminated by neutrons with energy ~ 5.8 MeV. PSD cuts are shown in red (dashed) and L threshold cuts are shown in blue (solid). Neutron events are below the PSD cut and gamma ray events are above. Counts are normalised to unit maximum bin intensity.

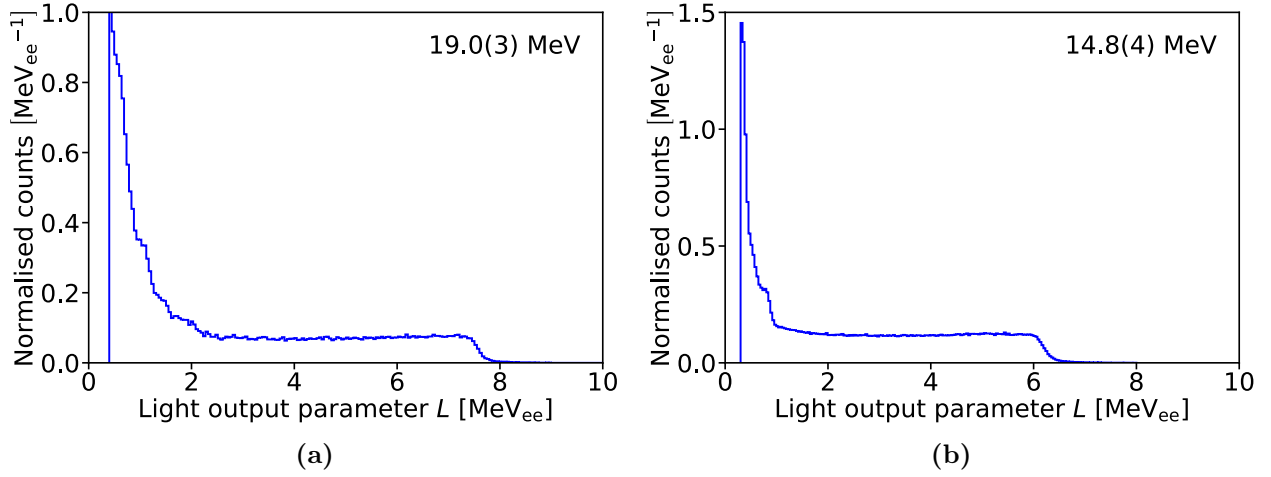


Figure 4.18: Neutron light output spectra measured by a $\varnothing$ 25 mm sphere of EJ-276 coupled to a SiPM for neutron fields with peak energy (a) 19.0(3) MeV and (b) 14.8(4) MeV at the PIAF Tandetron. The 19.0(3) MeV measurement was contaminated by neutrons with energy ~ 5.8 MeV. Spectra are normalised to unit integral.

In order to remove the ~ 5.8 MeV component from the 19.0(3) MeV measurement, the same time-of-flight techniques as described in Section 4.2.1 were used. The detector could only be placed 1018(1) mm away from the target due to the restrictions of the experimental hall, so the energy spectrum derived from time-of-flight had a low energy resolution, as shown in Figure 4.19 by the large spread of events around 19 MeV. The energy resolution was, however, sufficient to be able to separate the low and high energy contributions by discarding all events with energy less than 11 MeV. The neutron light output spectrum after the low energy contribution was removed is shown in Figure 4.20.

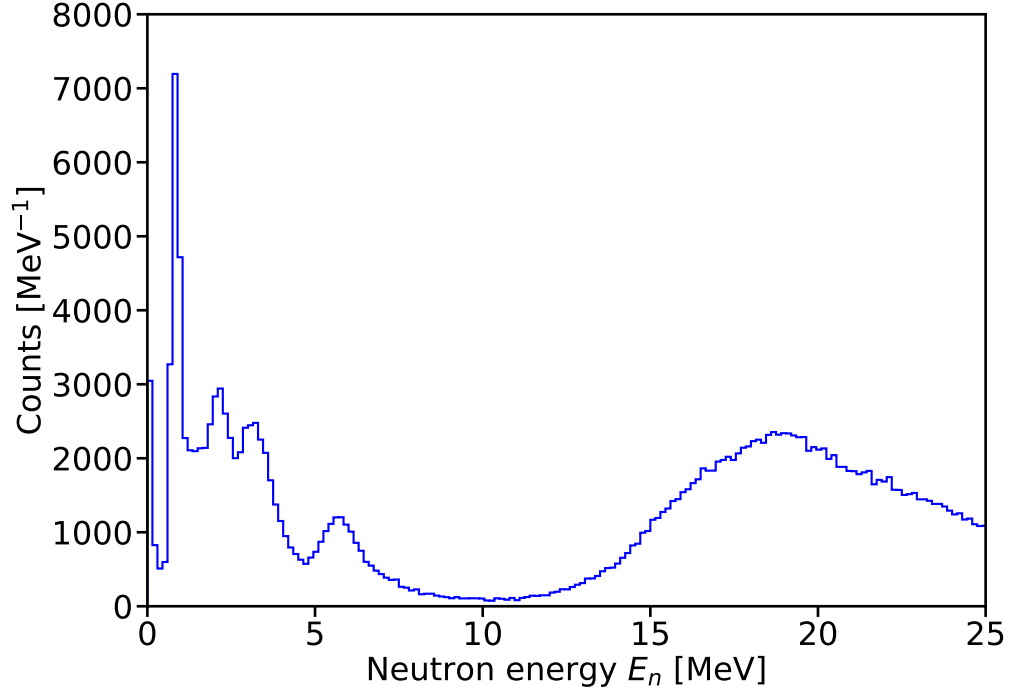


Figure 4.19: Neutron energy determined by time-of-flight for neutrons produced by 2674 keV deuterons irradiating a TiT target, measured at a target-detector distance of 1.018(1) m using a $\varnothing$ 25 mm sphere of EJ-276 coupled to a SiPM.

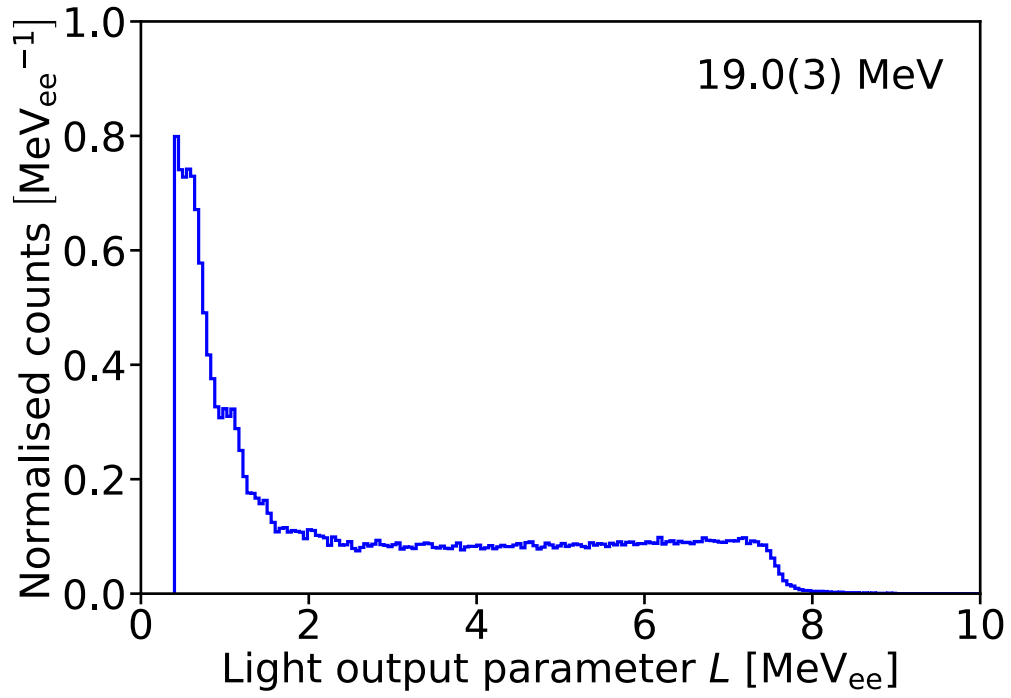


Figure 4.20: Neutron light output spectrum measured by a $\varnothing$ 25 mm sphere of EJ-276 coupled to a SiPM for neutron field with peak energy 19.0(3) MeV at the PIAF Tandetron facility. The ~ 5.8 MeV contamination was removed using the time-of-flight technique. Spectrum normalised to unit integral.

4.3 Verification of the time-of-flight calibration

The light output spectra measured at IRSN AMANDE were used to verify the accuracy of the time-of-flight calibration by comparing spectra from equivalent peak neutron energies. The 14.1(2) MeV spectrum was compared to the spectrum associated with neutrons with energy $14.0 \text{ MeV} \leq E_n \leq 14.2 \text{ MeV}$. The 0.2 MeV wide cut was chosen to provide a spectrum with enough events to have reasonable statistics. The 5.00(3) MeV and 2.50(2) MeV spectra were also compared to their time-of-flight counterpart, using the same width cut.

The comparisons are shown in Figure 4.21. The spectra were differentiated and a Gaussian function fit to the result in order to find the edge position, the results of which are in Table 4.3. All measurements fall well within one standard deviation of each other and are thus in good agreement.

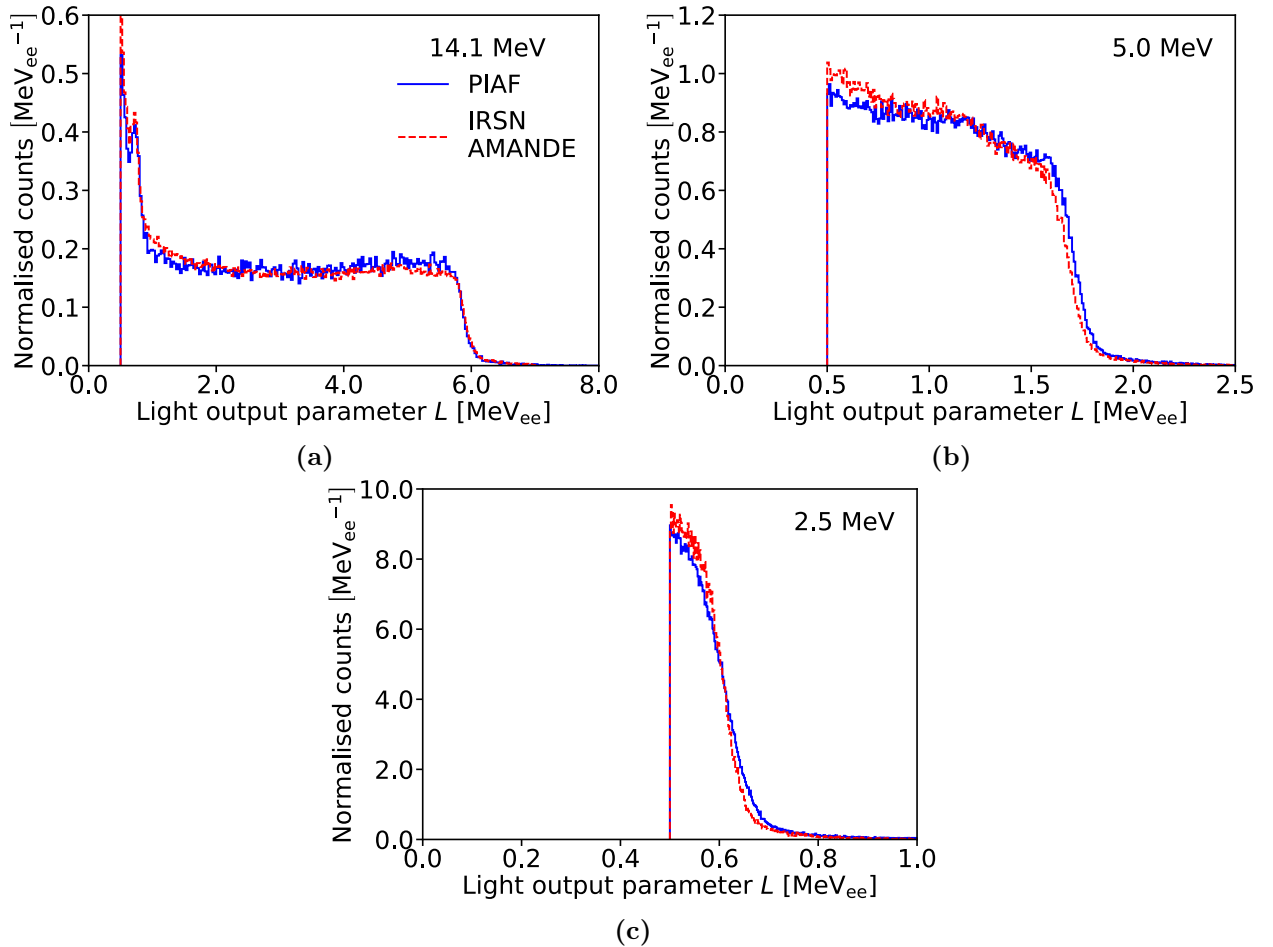


Figure 4.21: Comparison of light output responses between measurements made of monoenergetic neutron fields at IRSN AMANDE and 0.2 MeV cuts of the spectrum measured at PIAF using the time-of-flight technique, centred on the peak energy of the AMANDE measurement. Measurements made using a $\varnothing 25 \text{ mm}$ sphere of EJ-276 coupled to a SiPM at energies of (a) 14.1 MeV, (b) 5.0 MeV, and (c) 2.5 MeV. Spectra are normalised to unit integral.

Table 4.3: Proton recoil edge positions of the light output spectra shown in Figure 4.21, determined by taking the gradient of the light output spectrum and fitting a Gaussian function to the result, taking the centroid value to be the edge position.

Peak neutron energy [MeV]	AMANDE edge position [MeV _{ee}]	ToF edge position [MeV _{ee}]
14.1(2)	5.9(1)	5.85(9)
5.00(3)	1.68(7)	1.70(7)
2.50(2)	0.61(3)	0.61(5)

Chapter 5

Spectrum unfolding

The neutron lineshapes determined from the broad spectrum data formed the basis of the light output response functions used to perform spectral unfolding.

5.1 The GRAVEL algorithm

The multi-channel GRAVEL algorithm [53], which is part of the UMG-3.3 package [54], was used to perform the unfolding. It is a modified version of the SAND-II algorithm and takes an iterative approach, starting with a spectrum provided *a priori* and using a gradient descent method to approach a solution. The program uses the measured spectrum, response functions, an estimation of the measurement error, and the prior spectrum to generate the second iteration of energy spectrum. At each iteration, the energy spectrum is substituted for ϕ_j into

$$z_i = \sum_{j=1}^m R_{ij} \phi_j \quad (5.1)$$

and a χ^2/dof calculated between z (referred to as the “refolded spectrum”) and the measured light output spectrum. The iteration algorithm is designed such that the χ^2/dof tends to decrease with each iteration, which eventually leads to a solution. In practice, the program runs until the number of iterations reaches a user-defined value, or the χ^2/dof drops below a user-defined value.

The response functions R_{ij} in Equation (5.1) represent the response in the detector per unit fluence at the centre of the detector. In order to produce these from the lineshapes measured in the previous chapter, they must be normalised by the number of incident neutrons per cm^2 , also termed the fluence. For each lineshape associated with neutron energy E_n , the number of incident neutrons N_{in} is not known, but the number of detected neutrons N_{det} is, and these quantities are related by

$$N_{\text{det}}^{(E_n)} = N_{\text{in}}^{(E_n)} \epsilon^{(E_n)}. \quad (5.2)$$

The fluence is given by $\phi = N_{\text{in}}/A$ where A is the cross-sectional area of the detector, which is known, so to convert lineshapes into response functions for unfolding, the neutron detection efficiency $\epsilon^{(E_n)}$ needs to be known. A measurement of the neutron detection efficiency as a function of neutron energy would, however, require many measurements to be made at neutron metrology facilities, which is an expensive and time-consuming endeavour. Thus, simulation was used to estimate the neutron detection efficiency.

5.2 Simulation using Geant4

Geant4 is a Monte Carlo-based radiation transport simulation toolkit developed at CERN [55]. The toolkit was used to simulate the interaction of neutrons in EJ-276 scintillator in order to determine the detection efficiency as a function of neutron energy. Geant4 was chosen over the well-established NRESP code [56] as it is flexible with respect to the shape of the scintillating medium, rather than being restricted to cylindrical geometries. The detector system was modelled as a $\varnothing$ 25 mm sphere of EJ-276 with a $\varnothing$ 9 mm flat region, assuming that the surrounding infrastructure has a minimal attenuating effect. The material was modelled in the simulation by specifying the density and elemental composition in terms of number of atoms of a specific type per unit volume, which was obtained from the manufacturer’s website [17], shown in Table 5.1.

Table 5.1: Properties of the EJ-276 plastic scintillator required for the Geant4 modelling [17].

Density (g/cm ³)	1.099
No. of H atoms per cm ³ ($\times 10^{22}$)	4.674
No. of C atoms per cm ³ ($\times 10^{22}$)	4.944
No. of electrons per cm ³ ($\times 10^{23}$)	3.545

Monoenergetic neutrons were simulated from 1.00 MeV to 19.75 MeV in steps of 0.25 MeV. At each energy, 1 million neutrons were simulated incident on the detector at an incident angle of 0°, uniformly flooding the entire cross-sectional area. The number of primary neutrons was chosen to produce enough interactions that the resulting light output spectra are statistically significant. The type of recoiling particle, along with the energy it deposited in the scintillator, was recorded for each neutron interaction. Figure 5.1 shows the energy deposition spectra for each recoiling particle for 1 million incident neutrons with energy 14.1 MeV. The 1α and 3α responses are presented separately as they show up as distinct features in a measured light output spectrum. Recoiling deuterons were simulated but only 10 events were recorded so they are omitted from the figure.

Neutron detection efficiency ϵ is defined as the proportion of neutrons incident on the detector that interacted with the detector and produced light output greater than a chosen threshold. Thus, a conversion from simulated energy deposited in the detector to light output as measured was necessary.

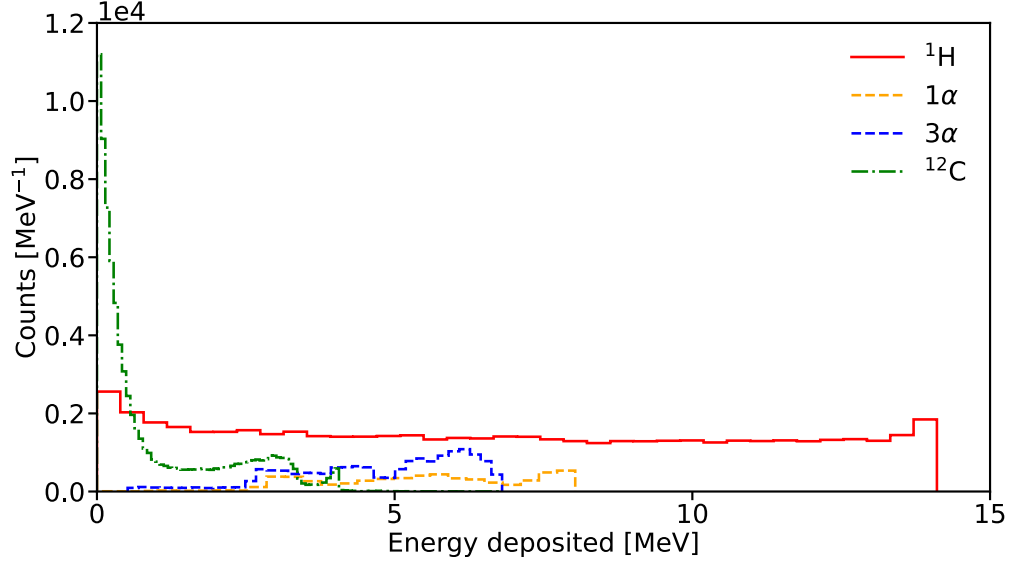


Figure 5.1: Energy deposition according to recoiling particle, simulated with Geant4 for 14.1 MeV neutrons incident on a $\varnothing$ 25 mm sphere of EJ-276.

5.2.1 Light output as a function of energy

The lineshapes measured at the PTB cyclotron facility were used to determine the light output as a function of the energy deposited in the scintillator by recoiling protons. For each slice in neutron energy, the edge position of the proton recoil continuum was determined, using the same procedure as was used for finding Compton edge positions for gamma ray calibration (Section 3.3.1). The position of the edge, in terms of light output L , was taken to be the light output for a recoiling proton with the same energy as the incident neutron, i.e. a proton scattering angle of $\theta = 0^\circ$. The same analysis was performed for the monoenergetic field measurements made at PIAF and AMANDE for comparison and the results are shown in Figure 5.2.

An empirical model for light output L as a function of proton energy deposition E , given in [57], was fit to the broad spectrum data, of the form:

$$L(E) = aE - b[1 - \exp(-cE^d)]. \quad (5.3)$$

The fit parameters are shown in Table 5.2, with an R^2 value of 0.999, which indicates a good fit, but it is clear from Figure 5.2 that there is some behaviour in the data which is not captured by the model as the model underestimates the data between 8–11 MeV and overestimates them above 14 MeV. It is believed that this behaviour is due to the saturation effect caused by the finite time taken for a microcell to process an incident photon and reset to be able to detect a subsequent photon. The model fits the broad spectrum data within one standard uncertainty, so it is considered adequate for this work.

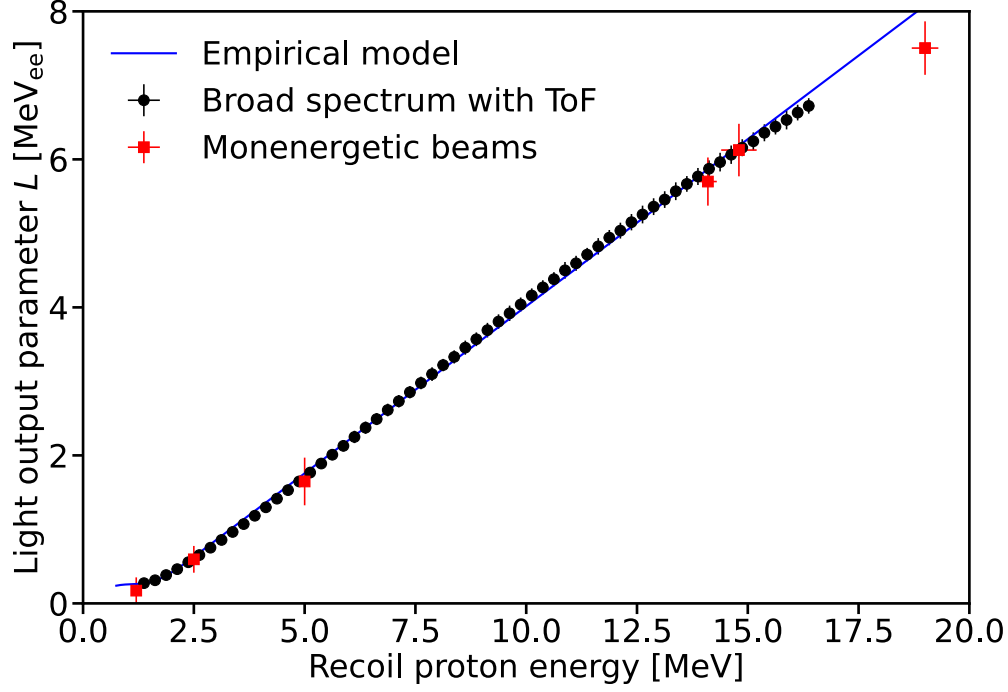


Figure 5.2: Light output as a function of recoiling proton energy for a $\varnothing$ 25 mm sphere of EJ-276 coupled to a SiPM. An empirical model from [57] is fit to the broad spectrum data.

Table 5.2: Fit parameters for Equation (5.3), determined by `scipy.optimize.curve_fit` for the data in Figure 5.2.

a	b	c	d	R^2
0.452(2)	0.50(2)	0.5(2)	2.8(9)	0.999

The saturation effect poses no issues to the spectroscopic ability in the < 20 MeV range as the proton recoil edge still increases significantly in L with increasing energy, however for higher energies it could pose an issue. Increasing the number of microcells in the light collection area may alleviate the issue for higher energies, which can be achieved either by increasing the number of SiPM sensors or using a sensor with a higher density of microcells.

5.2.2 Energy deposition to light output spectra

For each neutron interaction in the scintillator, the number, type, and energy deposition of each recoiling particle was recorded. The individual light output for each recoiling particle was calculated using the empirical model and fit parameters determined above and then summed to find the light output for each neutron event. For particles heavier than protons, the light output was then scaled according to measurements of light output as a function of recoiling particle energy for EJ-301 [58]. The result of this process for 14.1 MeV neutrons

is the green line (dot-dashed) in Figure 5.3, but there are some inconsistencies with the measured spectrum shown in blue (solid).

The 1α and 3α responses are not correct, and even scaling the response arbitrarily to fit the measured spectrum doesn't result in correct intensities or even correct shapes of the responses. This is due to the carbon breakup reactions that produce alpha particles not being well described by the data and models in the *G4ParticleHP* physics list. By including NRESP in the Geant4 physics list, the α -particle response can be correctly simulated [27], but this was unable to be implemented in the current work. For this reason, the α -particle contributions to light output spectra were discarded entirely. Responses to carbon nuclei were also discarded as they feature at lower light output values than α -particle responses and including them would lead to non-physical behaviour in the low L region. The exclusion of these responses was corrected for, described in Section 5.2.3.

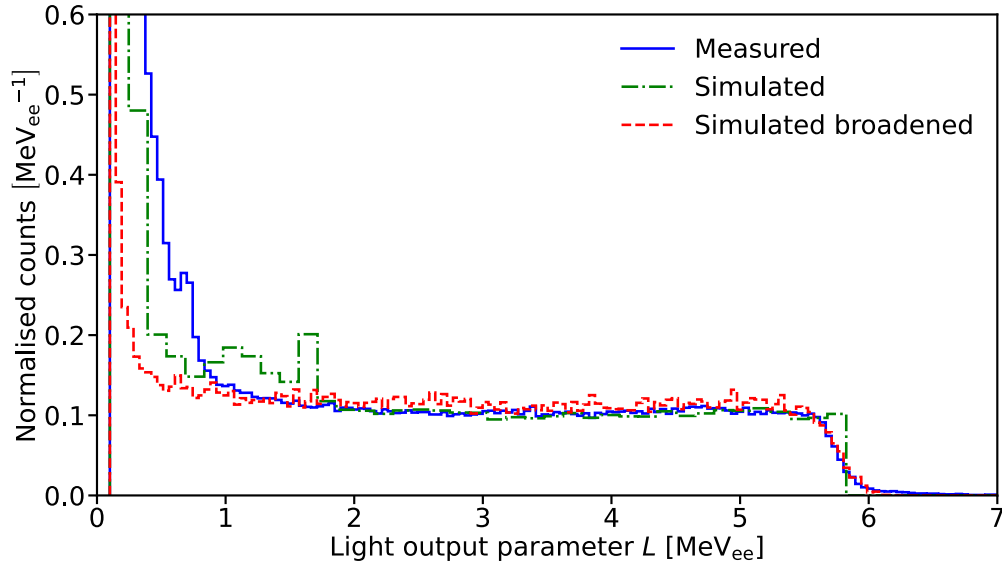


Figure 5.3: Light output spectrum associated with 14.1(2) MeV neutrons measured at AMANDE by a $\varnothing$ 25 mm sphere of EJ-276 coupled to a SiPM compared to the light output spectrum simulated using Geant4. The simulated spectrum before channel broadening is also shown, including carbon and α -particle responses. Spectra are normalised to match intensity in the proton recoil continuum.

The simulated light output spectrum also exhibits none of the channel broadening that is present in measured data, as can be seen by the sharp edge at 5.8 MeV in Figure 5.3. To include this broadening, the standard deviation of each measured proton recoil edge determined in Section 5.2.1 was recorded as $\sigma(L)$. For each event with simulated light output L_{sim} , a new light output value L'_{sim} was determined by sampling from a Gaussian distribution with centroid value L_{sim} and standard deviation $\sigma(L_{\text{sim}})$. These resampled light output values were histogrammed to produce the final simulated light output spectrum, shown in red (dashed) in Figure 5.3.

5.2.3 Neutron detection efficiency

At each simulated neutron energy, the detection efficiency was calculated as the proportion of neutrons incident on the detector that interacted with the detector and produced light output greater than a chosen threshold. Since the responses to alpha particles and carbon nuclei were discarded, the efficiency was calculated using an L threshold above any α -particle features in the spectra. For 20 MeV neutrons, a high threshold of about 2 MeV_{ee} is required. In order to include contributions below the α -particle threshold in the efficiency calculation, a scaling procedure between the EJ-276 detector and a well-characterised EJ-301 detector was used.

First, the relationship between the maximal light output for a given incident neutron energy for the EJ-276 detector (L_{276}) and a $\varnothing$ 5 cm $\times$ 5 cm cylinder of EJ-301 coupled to a PMT (L_{301}) was calculated, using light output responses determined using the NRESP simulation code [56]. The scaling factor (L_{301}/L_{276}) was determined by a fitting procedure to be 1.27, which allowed for light output thresholds placed on EJ-276 spectra to be converted to equivalent thresholds for EJ-301 spectra. With a light output threshold of 2.00 MeV_{ee} for the EJ-276 detector, and thus 2.54 MeV_{ee} for the EJ-301 detector, the efficiency was calculated using the respective simulated response functions by dividing the number of counts above the threshold by the number of incident neutrons.

The efficiency of the EJ-301 detector was higher than for EJ-276, so it was scaled down by a factor of 0.785, determined by a fitting procedure, the results of which are shown in Figure 5.4 alongside the EJ-276 efficiency. With the two efficiency curves matching well in regions where the Geant4 simulation is trusted, the EJ-301 NRESP responses were used, alongside the scaling factors determined above, to calculate the efficiency of the EJ-276 detector for a lower light output threshold.

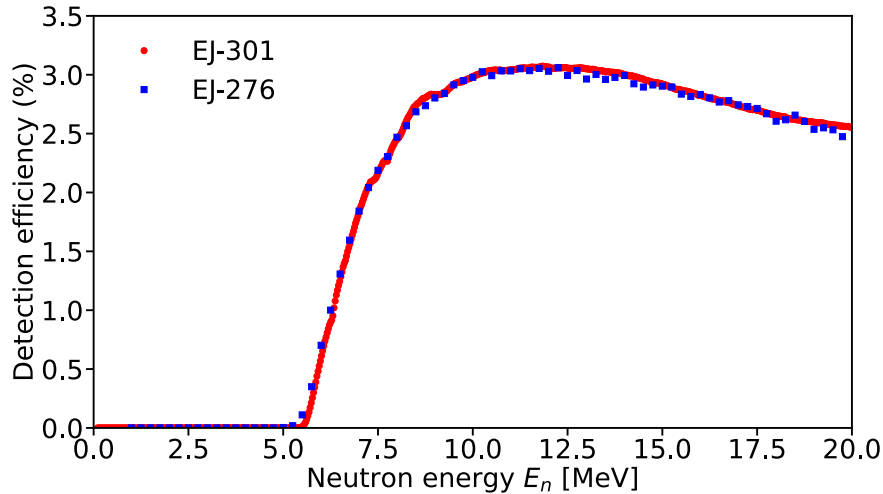


Figure 5.4: Neutron detection efficiency as a function of incident neutron energy, calculated using simulation: NRESP for EJ-301 and Geant4 for EJ-276. The EJ-301 efficiency has been scaled to match EJ-276. A light output threshold of 2.00 MeV_{ee} was used for EJ-276, equating to 2.54 MeV_{ee} for EJ-301.

A threshold of $0.250 \text{ MeV}_{\text{ee}}$, or an equivalent $0.318 \text{ MeV}_{\text{ee}}$ for EJ-301, was chosen as it is the same as the light output threshold used when separating neutron and gamma ray events (Section 4.2.1), which is the lowest possible light output threshold that could be applied to the EJ-276 detector. Efficiency was determined in the same way for the new threshold, shown in Figure 5.5. The curve is approximately smooth at low energy, but structure appears around 6 MeV, when the carbon reactions become relevant. In this way, the EJ-301 efficiency curve, which includes the α -particle responses, was scaled to be applicable to the EJ-276 detector.

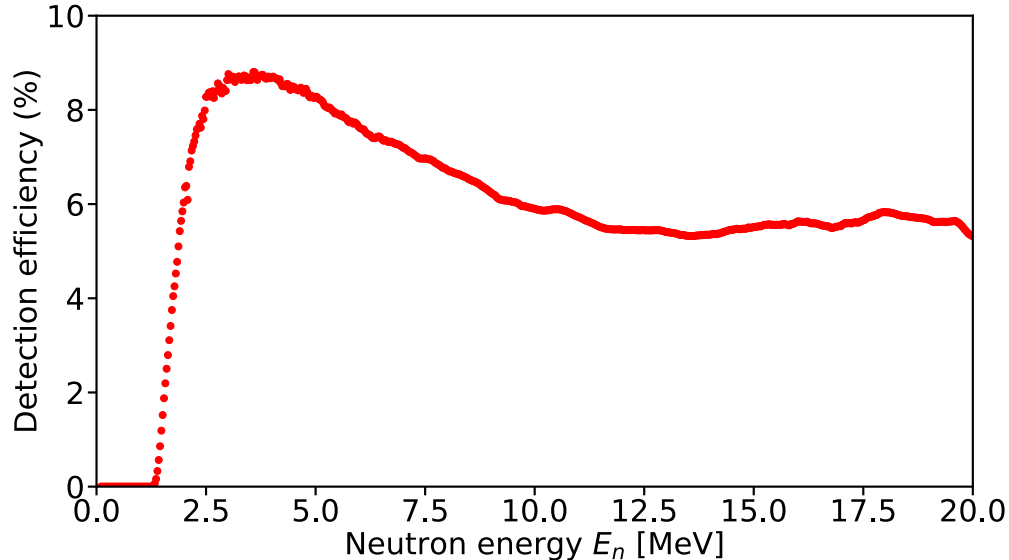


Figure 5.5: Neutron detection efficiency as a function of incident neutron energy, calculated using a combination of the NRESP and Geant4 simulation codes, for a $\varnothing$ 25 mm sphere of EJ-276 and a light output threshold of $0.25 \text{ MeV}_{\text{ee}}$.

Response functions were created from the measured lineshapes by dividing the bin intensities by the number of incident neutrons per cm^2 , i.e. the number of detected neutrons per cm^2 divided by the efficiency at the energy associated with that response. In the cases where the efficiency was zero ($< 1.35 \text{ MeV}$) this resulted in the response functions being zero everywhere.

5.3 Unfolding monoenergetic neutron fields

The light output spectra measured at AMANDE and PIAF for neutron fields with monoenergetic peak energies were unfolded to determine the incident neutron spectra. All monoenergetic measurements made at the two facilities were unfolded except for $19.0(3) \text{ MeV}$ and $1.20(2) \text{ MeV}$ as they do not fall within the range covered by the measured response functions.

Unfolding parameters are supplied to the UMG-3.3 program through a configuration file, with each line specifying a different parameter. Below is the file used for unfolding the $14.1(2) \text{ MeV}$ spectrum.

1	L_neutrons_14_1_MeV.ph	# Measured pulse height spectrum
2	neutron_response.rsp	# Neutron response functions
3	mono_14_1_MeV_unfolded	# Name of the output file
4	flat_350ch.flu	# Default spectrum
5	0.37,10.00	# Range of L to use in unfolding
6	2.0,15.0	# Range of E to use in unfolding
7	1.62	# Desired chi squared per dof
8	10000,100	# Num iterations, Iterations between display
9	3,1	# Energy bin structure, Refolded spectrum units
10	1	# 1 = Apply scaling factor
11	0	# Specify scaling factor (0 = Use GRAVEL factor)

The first line specifies the file containing the light output spectrum to be unfolded, in this case the spectrum measured at AMANDE. Line 2 specifies the file containing response functions. Line 3 specifies the name of the file in which the unfolded energy spectrum is output. Line 4 specifies the default spectrum. In this case, a flat default spectrum with bins of width 0.06 MeV ranging from 0.20 MeV to 19.97 MeV was used. Line 5 specifies, in light output units (in this case MeV_{ee}) the lower and upper bounds of the light output spectrum that should be considered in the unfolding process. Line 6 specifies, in MeV units, the lowest and highest energy of the response functions that will be used.

The GRAVEL algorithm is applied iteratively until one of two conditions are met: either the number of iterations reaches a user-defined value, specified as the first entry in line 8; or the χ^2/dof between the reconstructed light output spectrum and the input measured spectrum falls below a certain value, specified in line 7. In practice, the program was allowed to run for 10000 iterations and the χ^2/dof output to a file every 100 iterations (specified as the second entry in line 8). The difference between each consecutive χ^2/dof was calculated and the desired χ^2/dof was chosen as the value for which the difference between consecutive values fell below 1% of the current value, as shown in Figure 5.6. The program was then run again using this value.

Line 9 specifies the bin structure to be used for the final energy spectrum as well as the vertical units of the final refolded light output spectrum. For all unfolded spectra in this work, the final energy spectrum was set to mirror the binning structure of the response functions and the refolded light output spectrum set to have the same units as the input spectrum.

The final two parameters specify whether a scaling factor should be applied to the default spectrum and what the scaling factor should be. For this work, the scaling factor determined by the program was used. After the first iteration of the algorithm, the χ^2/dof is calculated and the default spectrum is scaled vertically such that the χ^2/dof is minimised. This scaling is then applied for all subsequent iterations.

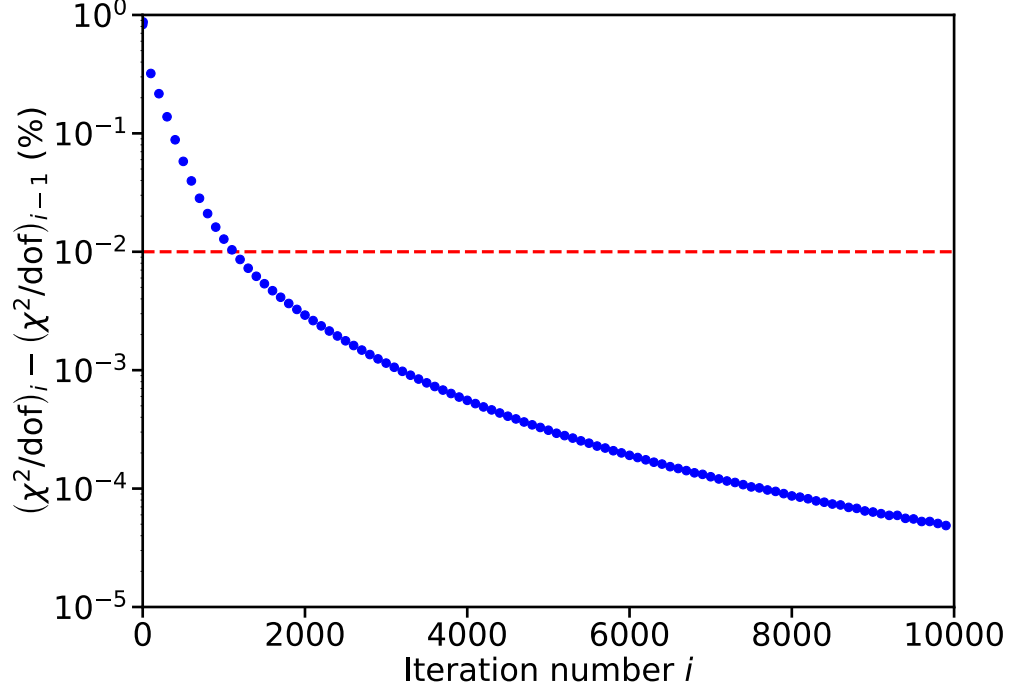


Figure 5.6: Percentage difference in χ^2/dof value for subsequent iterations of the GRAVEL algorithm, implemented on a measured light output spectrum for 14.1(2) MeV neutrons using the UMG-3.3 package. The threshold value of 1% is shown in red (dashed).

Table 5.3 shows the parameters set in the configuration files for the unfolding of measurements of the monoenergetic neutron fields. The lower bound on the L range was partially dictated by the range covered by the response functions, which were created with an L threshold of 0.25 MeV_{ee}. However, during the unfolding process, a lower bound of 0.37 MeV_{ee} was found to produce more stable unfolding results. The lower bound on the E range was dictated by the lowest energy for which the neutron edge could be identified, given the lower L bound. The upper bounds for both L and E were set to include all the data and allow for unfolding of the expected energies. Figure 5.7 shows the measured light output spectra compared to the refolded spectra associated with the solution neutron spectra.

Table 5.3: Parameters used in unfolding the neutron energy spectra from monoenergetic neutron measurements.

Neutron energy [MeV]	L range [MeV _{ee}]	E range [MeV]	Desired χ^2/dof
2.50	[0.37, 1.0]	[2.0, 3.5]	176
5.00	[0.37, 3.0]	[2.0, 6.0]	3.54
14.1	[0.37, 10.0]	[2.0, 15.0]	1.62
14.8	[0.37, 12.0]	[2.0, 16.0]	7.48

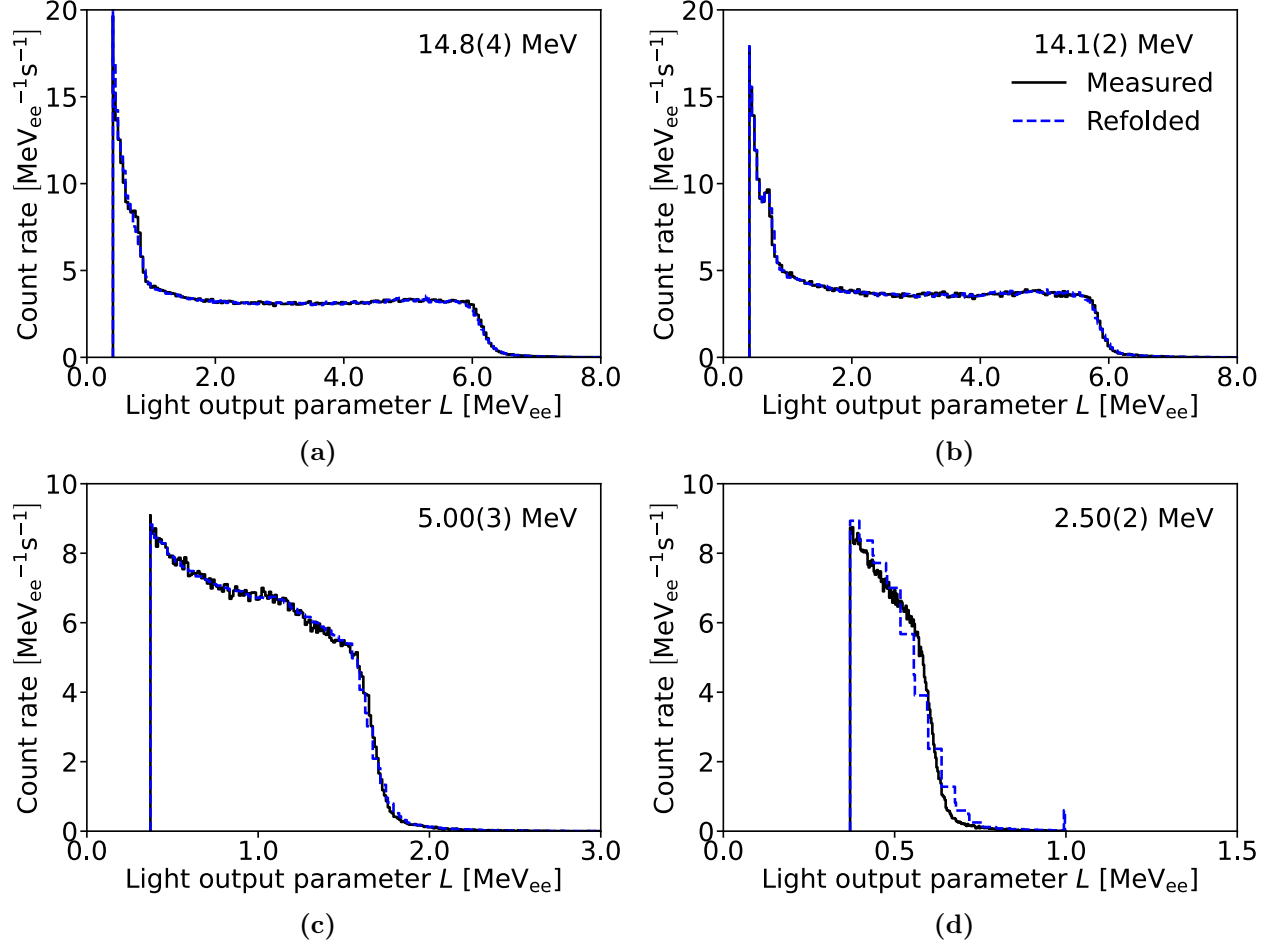


Figure 5.7: Light output spectra associated with measurements of neutron fields with monoenergetic peak energies of (a) 14.8(4) MeV, (b) 14.1(2) MeV, (c) 5.00(3) MeV, and (d) 2.50(2) MeV compared to the refolded spectrum produced by GRAVEL. Measurements made by a $\varnothing$ 25 mm sphere of EJ-276 coupled to a SiPM.

Figure 5.8 shows the resulting neutron energy spectra, normalised to unit integral and compared to the peak energy of the neutron fields that were measured. The unfolded spectra are most intense at the peak energies of the measured fields within the one standard uncertainty of the peak energies (shown as shaded regions around the dashed lines). For this reason, the detector is considered to perform well as a spectrometer for monoenergetic neutron fields.

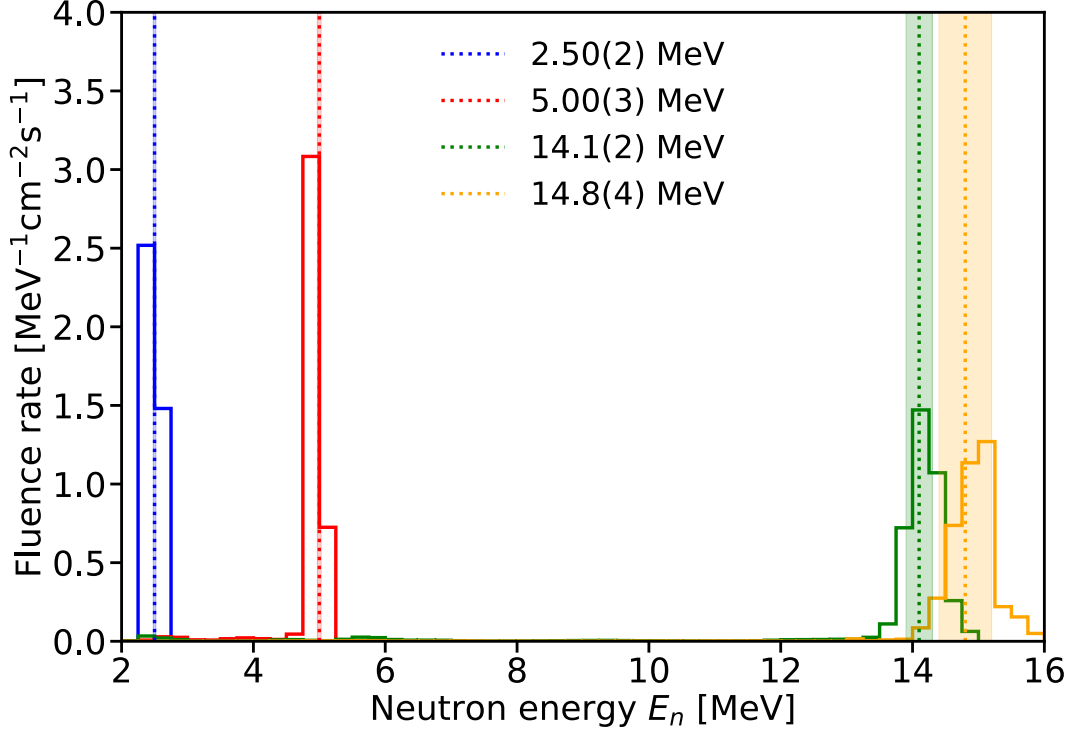


Figure 5.8: Neutron energy spectra unfolded from light output spectra associated with measurements of monoenergetic neutron, made with a $\varnothing$ 25 mm sphere of EJ-276 coupled to a SiPM. Uncertainties on the peak field energies are shown as the shaded regions around the dashed lines.

5.4 Unfolding an AmBe neutron spectrum

In order to test the detector system as a spectrometer for analysing broad spectrum neutron fields, the AmBe source at the n-lab was measured and the light output spectrum unfolded.

Neutrons are produced in AmBe sources by the reaction of the ^9Be with an α -particle, which was emitted by the ^{241}Am decay. An atom of ^{13}C is produced, which emits a neutron to become ^{12}C , in one of three states: the ground state, the 4.43 MeV state, or the 7.66 MeV state [59]. The rates of production of these states depends on the energy of the incident α -particle, which itself can depend on the fabrication of the AmBe neutron source itself. The resulting ^{12}C states also result in different neutron energy distributions, the combination of which makes up the AmBe neutron spectrum. The main peaks of the AmBe neutron spectrum as calculated [59] are at 2.35 MeV, 3.10 MeV, 5.00 MeV, 6.20 MeV, 7.80 MeV, 8.00 MeV, and 9.80 MeV.

The AmBe neutron light output spectrum measured at the n-lab in Section 3.3.2 was unfolded using GRAVEL with the parameters specified in Table 5.4. The ISO recommended AmBe neutron energy spectrum [44] was used as the default spectrum, shown in black in Figure 5.10.

Table 5.4: Parameters used in unfolding the neutron energy spectrum from the measurement of an AmBe source.

L range [MeV _{ee}]	E range [MeV]	Desired χ^2/dof
[0.25, 6.0]	[1.6, 11.5]	0.8

Figure 5.9 shows the measured light output spectrum compared to the refolded spectrum and Figure 5.10 shows the unfolded neutron energy spectrum compared to the ISO standard AmBe spectrum [44] as well as a previous measurement performed using a $\varnothing$ 5 cm $\times$ 5 cm cylinder of EJ-301 coupled to a PMT, which is the reference detector for the n-lab [41], for a similar but not identical AmBe source. The ISO spectrum and the EJ-301 spectrum have been re-binned to the same binning structure of the unfolded spectrum in the interest of comparing the spectra, as their original binning was finer than the resolution of the response functions. The difference between the EJ-301 spectrum and the EJ-276 spectrum is shown below the unfolded spectra.

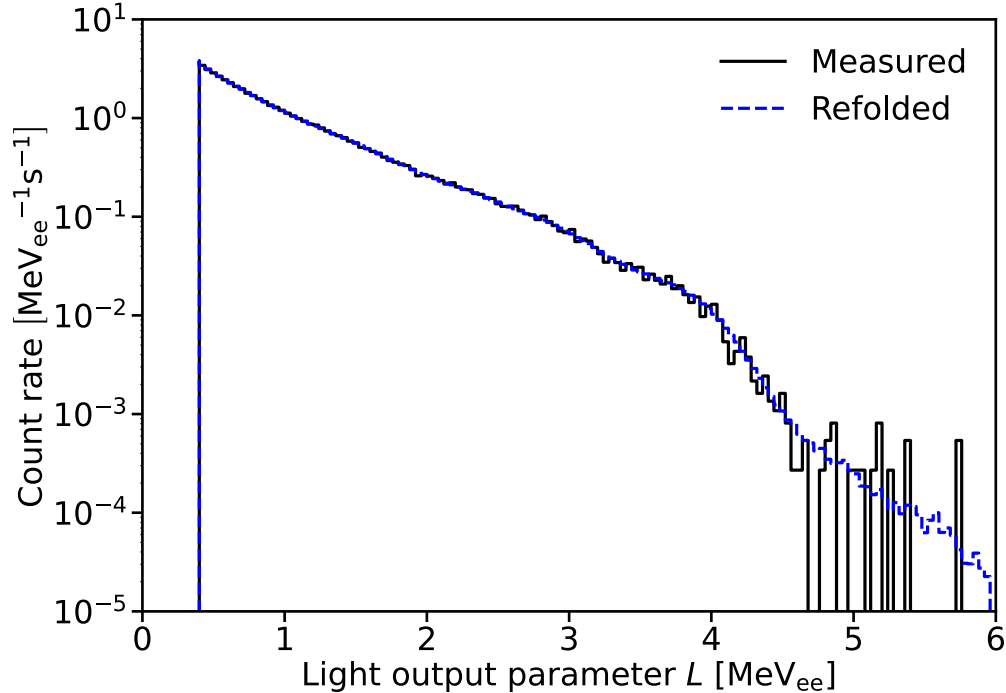


Figure 5.9: Neutron light output spectrum of an AmBe source measured by a $\varnothing$ 25 mm sphere of EJ-276 coupled to a SiPM, compared to the refolded spectrum produced by the unfolding process.

The EJ-276 unfolded energy spectrum matches the measurement made with the EJ-301 detector very well, especially in the regions where the reference detector’s measurement differs from the ISO spectrum (6–8 MeV and 3–4 MeV). The spectra appear to have systematic differences in two regions (2–3 MeV and 5–6 MeV), as seen in the residuals plot. This may be due to the procedure used to determine the detection efficiency for EJ-276, as it assumed the cross-sections of neutron interactions with carbon and alpha

particles was the same between EJ-301 and EJ-276, or because of differences in the construction of the two AmBe sources. A two-sample Kolmogorov-Smirnov (KS) test [60] was used to evaluate the similarity of the EJ-276 and EJ-301 spectra, finding a KS statistic of 0.6 and a p-value of 1.0. This indicates that the two spectra are extremely likely to be drawn from the same distribution.

Additionally, while the two spectra measured in the n-lab differ from the ISO spectrum in terms of bin intensity in some regions, they feature peaks in the same positions as the ISO spectrum, which also align with the calculated peak positions [59]. The difference in intensity of the peaks may be a result of differences in the construction of the sources used in the measurements, which is known to affect the energy spectrum [61]. Future work will extend the efficiency calculation to lower energies and the response functions to higher energies to allow for more complete unfolding capabilities in the 1–20 MeV region.

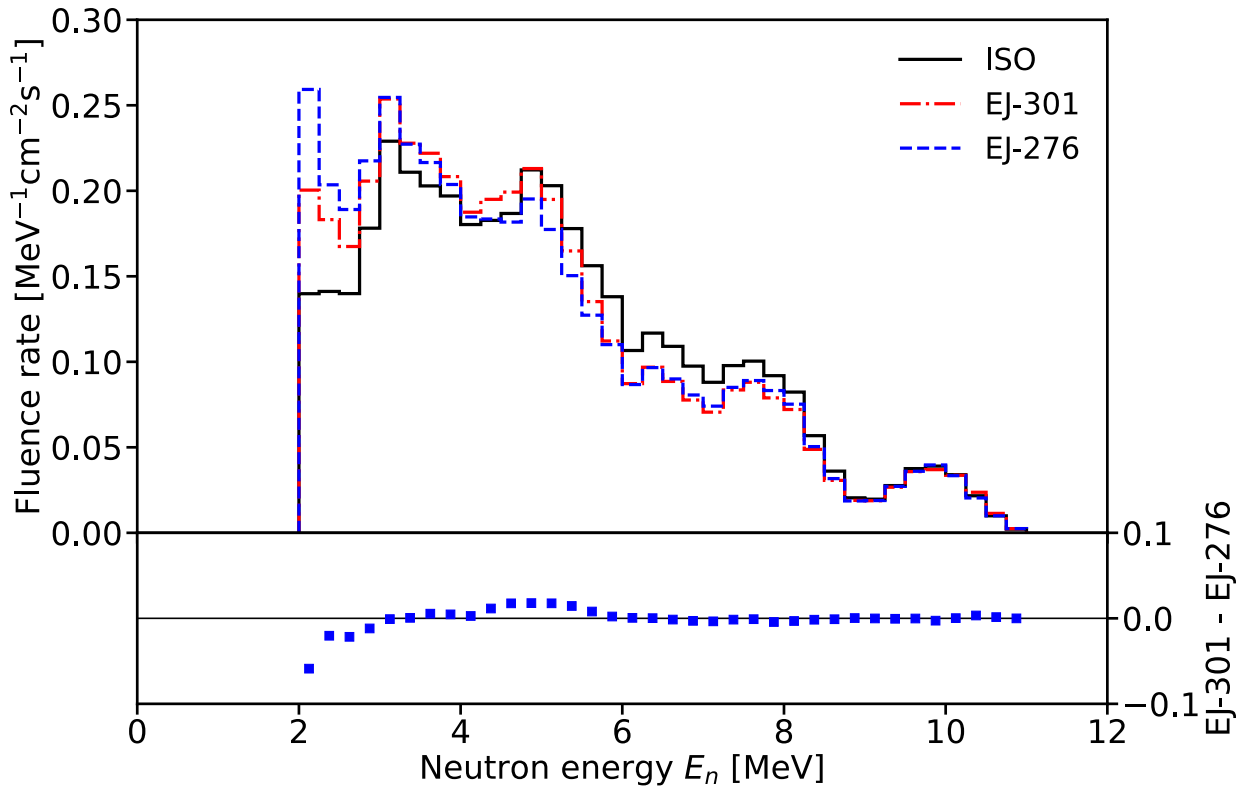


Figure 5.10: Unfolded neutron energy spectrum of an AmBe source, measured by a $\varnothing$ 25 mm sphere of EJ-276 coupled to a SiPM and unfolded using GRAVEL. The measured spectrum is compared to the ISO standard AmBe spectrum specified by [44] as well as a measurement made using the EJ-301 reference detector at the n-lab [41]. Difference between the EJ-301 spectrum and the EJ-276 spectrum is shown below.

Chapter 6

Conclusion

A compact neutron spectrometer was constructed from a $\varnothing$ 25 mm sphere of EJ-276 PSD-capable plastic scintillator coupled to a C-series silicon photomultiplier from onsemi mounted on a custom PCB. A CAEN DT5730S desktop digitiser was used for data acquisition, to allow for offline processing of events and optimisation of analysis techniques. The spherical design was chosen to reduce the dependence of the detector response on the direction of incident radiation and the size was chosen to be similar to cylindrical detectors often used for neutron spectroscopy up to 20 MeV. The detector system was developed at the n-lab in the Department of Physics at the University of Cape Town, optimising the construction and analysis techniques. The dependence on the direction of incident radiation was also tested at the n-lab, finding that the detector system performed well within accepted tolerances for a neutron spectrometer in terms of the light output response as well as the detection efficiency.

The detector system was further characterised at AMANDE and PIAF, using the neutron fields with monoenergetic peak energies produced at both facilities and the broad spectrum neutron field produced at the latter. The broad spectrum beam was used in conjunction with the time-of-flight technique to measure the energy of the incident neutron associated with a detector event, which allowed for the creation of neutron light output response functions. The monoenergetic measurements were used to verify the accuracy of the time-of-flight calibration as well as to calibrate the Monte Carlo-based Geant4 simulation of neutron detection efficiency, which was used in the production of the response functions. The performance of the detector was benchmarked against a detector made of a $\varnothing$ 25 mm $\times$ 25 mm cylinder of EJ-276 mounted on a PMT — a more traditional spectrometer. The spherical detector was seen to have better light output edge resolution and better pulse shape discrimination ability.

The Geant4 simulation toolkit was used to simulate light output responses for the detector in order to calculate the neutron detection efficiency of the detector, but it was unable to reproduce the α -particle production mechanisms that form part of the neutron light output responses at low light output values. For this reason, response functions for a detector made from EJ-301 liquid organic scintillator, previously simulated using the NRESP code, were

used to produce an efficiency measurement for the EJ-276 detector by scaling the light output and efficiency values in energy regions where the Geant4 simulations were reliable.

With efficiency incorporated into the measured response functions, the UMG-3.3 unfolding package, with the GRAVEL algorithm, was used to unfold the incident neutron spectra associated with measurements of monoenergetic neutron fields as well as the field associated with an AmBe neutron source. The unfolding technique performed well in both cases, producing neutron energy spectra similar to the expectations.

6.1 Recommendations and future work

A number of future developments have been considered for the detector that could extend the range of the spectrometer down to lower energies (< 2 MeV), and also into the high-energy neutron region (> 20 MeV).

The lower energy limit in the present detector is dictated by the light output threshold below which reliable separation between neutrons and gamma rays is no longer possible. Although it is possible to make some assumptions regarding the distribution of neutron and gamma ray events in the low light output region, it was not explored in this work. An alternative, hardware-based solution could be to split the SiPM output, increase the gain associated with one of the pulses, and then acquire both the high- and low-gain pulses. As the two pulses would be correlated, the high-gain pulses could then be used for separation in the low light output region. Preliminary investigations suggest that a lower energy threshold of around 0.5 MeV will be possible in the neutron energy spectrum with this implementation with a factor 4 increase in gain. Extending the range of the spectrometer below a lower energy limit of 0.5 MeV is likely to require the use of more than one detector, the addition of absorbers and moderators, or using a doped version of EJ-276 such as the Li-doped variant which has very recently been reported [62].

To improve the quality of spectrum unfolding below 20 MeV by introducing Geant4 simulated response functions the issues around $^{12}\text{C}(\text{n}, \text{X}\alpha)$ reactions need to be resolved. The NRESP Monte Carlo simulation code [56] is well established, and considered highly reliable, in describing the light output response of organic scintillators to neutrons with energies up to 20 MeV, however it is restricted to traditional cylindrical detector geometries. There have been recent developments to include “NRESP mode” within Geant4 [27], which will be explored for the next phases of this work for the modelling of a spherical detector.

Progress towards a spectrometer for measurements up to 120 MeV is already underway, making use of a larger sphere coupled to an array of 4 SiPMs to be used for measurements at altitude and in space, and around accelerator facilities. Such a detector would be appropriate for routine measurements on board aircraft through the Cosmic On Air project [63], which aims to increase the number of measurements made of gamma ray and neutron radiation at aviation altitudes. To ensure that the detector system is robust to changes in temperature and pressure, and mechanical shock and vibration, more

permanent alternatives to the EJ-550 optical grease need to be explored, such as the EJ-500 optical cement.

The development and characterisation of a novel, compact, spherically-shaped neutron spectrometer for energies < 20 MeV has been presented. The detector was constructed from EJ-276 plastic scintillator coupled to a silicon photomultiplier, with digital data acquisition. The detector exhibits excellent pulse shape discrimination capabilities as well as outstanding light collection leading to superior light output edge resolution when compared to traditional geometries. Neutron light output response functions were measured and used to unfold neutron energy spectra from monoenergetic sources as well as an AmBe neutron source, with good accuracy and energy resolution. The brilliant light transport to the point of collection at the silicon photomultiplier suggests that the device would be useful in both high and low count rate environments, and warrants further modelling.

Light in *spherical* plastic, it's fantastic.

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Appendix A

Comparison to a PMT-based detector system

In order to benchmark the performance of the spherical system, the measurements of neutron fields with monoenergetic peak energies made at AMANDE and PIAF were repeated with a detector made of a $\varnothing$ 25 mm $\times$ 25 mm cylinder of EJ-276 mounted on a $\varnothing$ 25 mm Scionix 1M-E1-X photomultiplier tube. The cylindrical detector's response was calibrated with ^{137}Cs as a gamma ray source.

Figure A.1 shows a comparison between the light output spectra associated with the gamma ray calibration measurement of a ^{137}Cs source. A slight enhancement in the intensity at the Compton edge can be seen for the spherical detector, which hints towards better light output resolution, but more investigation is necessary.

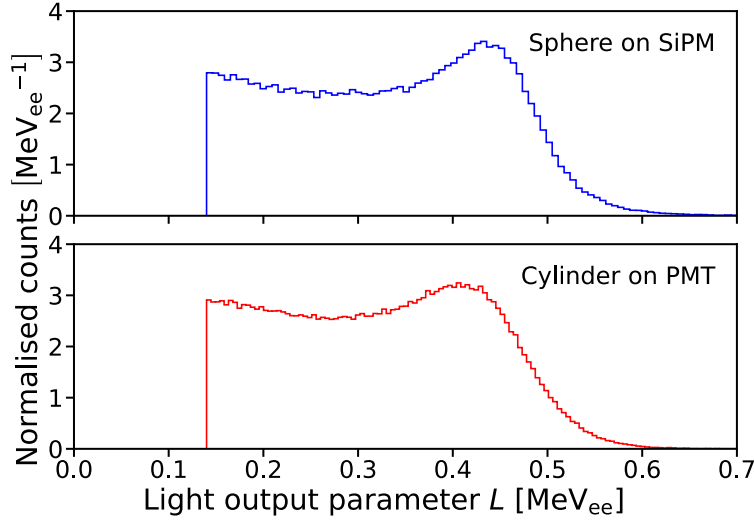


Figure A.1: Light output spectra associated with a ^{137}Cs gamma ray source, measured at IRSN AMANDE by a $\varnothing$ 25 mm sphere of EJ-276 mounted on a SiPM (top) and a $\varnothing$ 25 mm $\times$ 25 mm cylinder of EJ-276 mounted on a PMT (bottom). Spectra are normalised to unit integral.

The L - S spectra associated with the measurements of 14.1(2) MeV neutrons are shown in Figure A.2. The spherical detector clearly has better separation of the neutron and gamma ray loci. This is quantified by a calculation of the figure of merit for each spectrum, for events with $0.8 \text{ MeV}_{ee} < L < 1.2 \text{ MeV}_{ee}$, which resulted in 1.74(1) for the spherical detector and 0.924(7) for the cylindrical. The neutron light output is, however, lower for the spherical detector, as shown in Figure A.3 after PSD cuts and L thresholds have been applied.

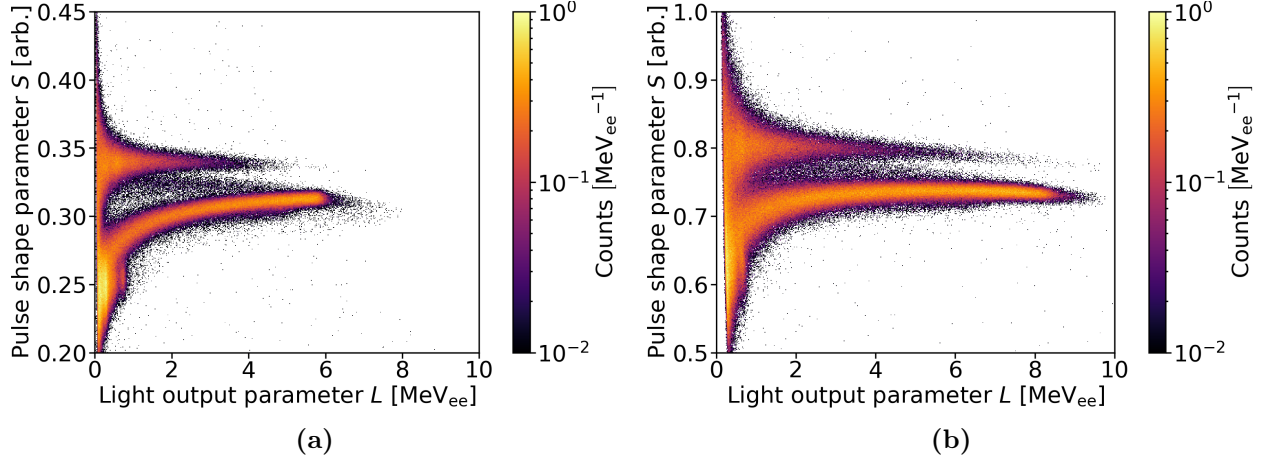


Figure A.2: Events as a function of L and S for gamma rays and neutrons produced by 432 keV deuterons incident on a TiT target, producing 14.1(2) MeV neutrons at 90° to the beam angle. Measurements made at the IRSN AMANDE facility by (a) a $\varnothing$ 25 mm sphere of EJ-276 mounted on a SiPM and (b) a $\varnothing$ 25 mm $\times$ 25 mm cylinder of EJ-276 coupled to a PMT. Counts are normalised to unit maximum bin intensity.

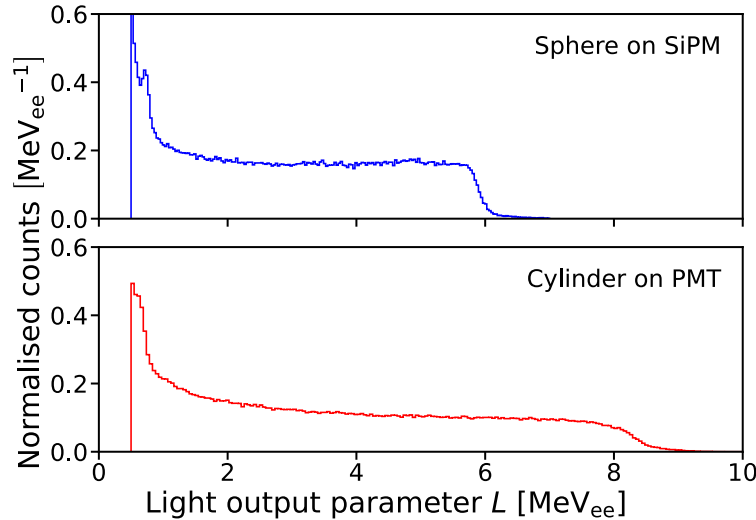


Figure A.3: Light output spectra associated with 14.1(2) MeV neutrons, measured at IRSN AMANDE by a $\varnothing$ 25 mm sphere of EJ-276 mounted on a SiPM (top) and a $\varnothing$ 25 mm $\times$ 25 mm cylinder of EJ-276 mounted on a PMT (bottom). The difference in light output is a result of the saturation effect present at high light output in SiPMs. Spectra are normalised to unit integral.

The drop in maximum light output for a given incident neutron energy is a result of the use of a SiPM instead of a PMT. Figure A.4 shows a comparison between event pulses from each detector for events of the same calibrated light output value, for both low and high light output events. Also shown are the positions of the relative long integral time. For both, it can be seen that the SiPM pulse does not return to the baseline by the time of the end of the long integral, but for high light output events, the amount “missing” from the pulse integral is much larger, so it results in a greater proportional reduction in the light output. Thus, it is expected that the light output spectrum for a lower peak energy neutron field will match better between the two detector systems.

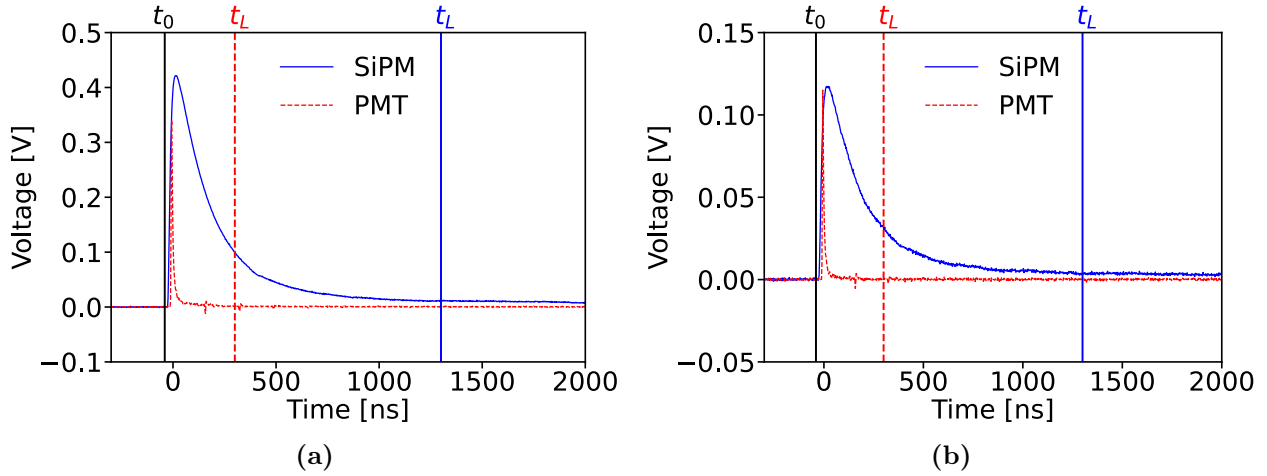


Figure A.4: An example detector pulse from a $\varnothing$ 25 mm sphere of EJ-276 coupled to a SiPM (blue solid) and a $\varnothing$ 25 mm $\times$ 25 mm cylinder of EJ-276 coupled to a PMT (red dashed) for events with light output of (a) 5 MeV and (b) 1 MeV. Shown are the endpoints of the long integral window for each detector system.

The lower light output at higher neutron energies does not affect the spectroscopic abilities of the spherical detector system. Previous work at UCT [64] has shown that a non-optimised choice of integral length for a spectrum measurement can lead to inaccuracies in the unfolding of that measurement when the response functions were created using the traditional method of processing the dynode pulse and extracting the pulse height. In this work, the response functions were created with precisely the same integral length as the spectra were measured with, so the system is internally consistent, hence there is no loss of accuracy in the unfolding process. For this reason, the underestimation is not considered an issue in this work.

Figure A.5 shows the L - S spectra associated with the measurement of 5.00(3) MeV neutrons. Once again the separation between neutron and gamma ray loci is clearly better for the spherical detector, but it can be seen that the neutron locus ends at about the same light output value for both spectra. This can be seen more clearly in Figure A.6, as well as the sphere’s better light output resolution, evidenced by the sharper edge of the proton recoil continuum.

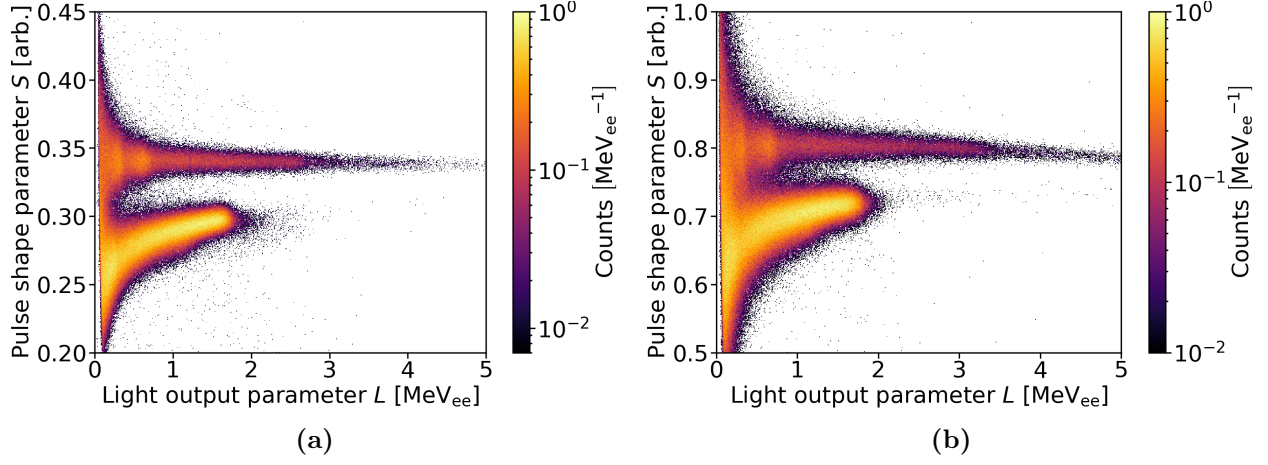


Figure A.5: Events as a function of L and S for gamma rays and neutrons produced by 432 keV deuterons incident on a TiT target, producing 5.00(3) MeV neutrons at 90° to the beam angle. Measurements made at the IRSN AMANDE facility by (a) a $\varnothing$ 25 mm sphere of EJ-276 mounted on a SiPM and (b) a $\varnothing$ 25 mm $\times$ 25 mm cylinder of EJ-276 coupled to a PMT. Counts are normalised to unit maximum bin intensity.

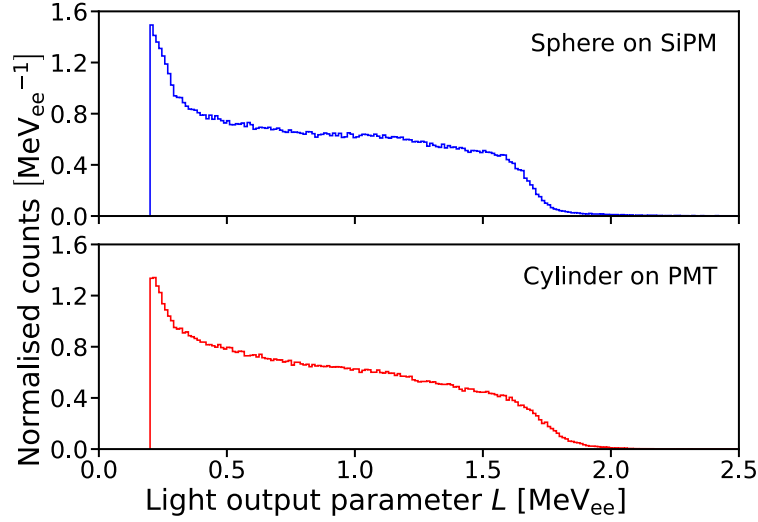


Figure A.6: Light output spectra associated with 5.00(3) MeV neutrons, measured at IRSN AMANDE by a $\varnothing$ 25 mm sphere of EJ-276 mounted on a SiPM (top) and a $\varnothing$ 25 mm $\times$ 25 mm cylinder of EJ-276 mounted on a PMT (bottom). Spectra are normalised to unit integral.

The figure of merit was calculated for the 5.00(3) MeV measurements for 0.2 MeV_{ee} wide slices in L , as a function of light output. The result is shown in Figure A.7 and the spherical detector can be seen to have a better FoM over the entire range.

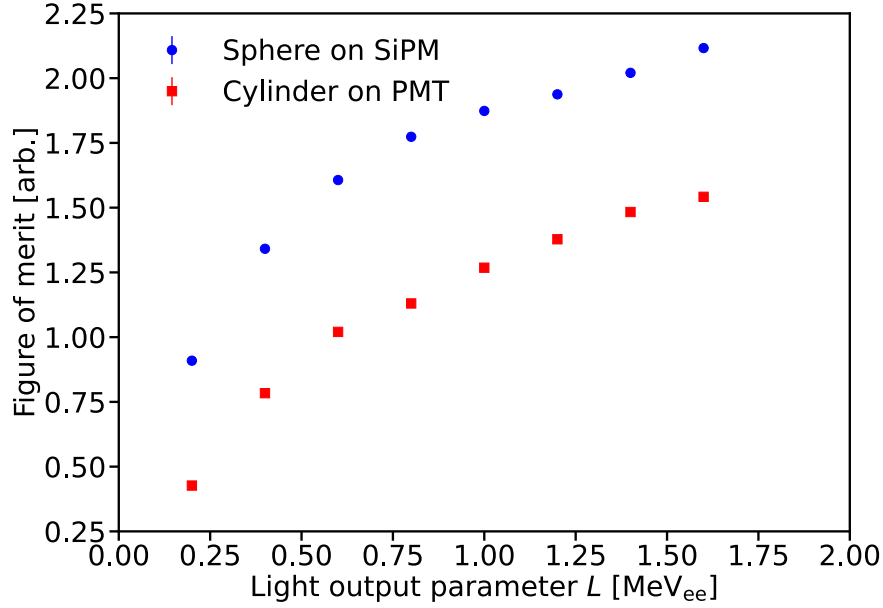


Figure A.7: Figure of merit as a function of light output L , for slices in L of width 0.2 MeV_{ee}, for the spherical and cylindrical detectors.

The light output resolution was determined for both detectors, for both measurements. A Gaussian function was fit to the gradient of the light output spectrum and the resolution calculated as the ratio of the full-width half maximum to the centroid value as determined by the fitting procedure. Table A.1 shows the resolution calculated for the proton recoil edge for both detectors, for both neutron energies. The SiPM-based detector exhibits better light output edge resolution, even for the 5.00(3) MeV measurement where the proton recoil edge is in approximately the same position for both detectors.

Table A.1: Light output resolution for the spherical and cylindrical detector calculated using the proton recoil edge from measurements of monoenergetic neutron fields.

Detector	5.00(3) MeV	14.1(2) MeV
Sphere on SiPM	10(3)%	5(2)%
Cylinder on PMT	15(6)%	9(2)%