Development of a Capture-Gated Fast Neutron Detector with Pulse Shape Discrimination using Digital Pulse Processing

By

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Summary

This study explores the use of digital pulse processing techniques for n/γ pulse shape discrimination (PSD) in liquid scintillators, and the application of these techniques to a capture-gated fast neutron monitor developed using an enriched $^{10}$B-loaded liquid scintillator (BC523A). The motivation for this study has been to develop a computationally-fast digital PSD algorithm, which can be used to detect a weak neutron flux in the presence of a strong gamma ray background and to assess its suitability for use as a portable neutron monitor for fast neutron dosimetry.

BC523A can operate as a full-energy neutron spectrometer when used in the ‘capture-gated’ mode, where a characteristic capture time is observed between the proton recoil and neutron capture pulses, thus producing a very clean signature for those fast neutrons which are completely moderated within the detector volume. The use of digital waveform capture of this double-pulse sequence is a powerful technique that allows acquiring both the time-stamped pulse amplitudes and the capture lifetime in a single data set. The capture-gated performance of a 105 cm$^3$ BC523A detector was investigated using fast neutrons from an Am-Be source. The measured mean neutron capture time in BC523A was 470±80 ns, which is a factor of 5 shorter than that reported for liquid scintillators loaded with natural boron. Due to its limited neutron detection efficiency, an extension of this technique to a large volume (685 cm$^3$) BC523A was developed, and provided an efficiency increase by a factor of 7. The efficiency enhancement was modelled using MCNP-4C.

Good n/γ separation was obtained using digital PSD applied to BC523A. The PSD figure-of-merit (FOM) was investigated for various organic scintillators, and compared between digital and analogue pulse processing techniques. The application of digital PSD to the capture-gate detection mode was investigated, as an additional method for suppression of gamma sensitivity.

Key words: Digital pulse shape discrimination, capture-gated neutron detection, boron loaded liquid scintillator, waveform digitiser.

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Contents

Summary ................................................................................................. ii
Acknowledgements .................................................................................. iii
Contents ................................................................................................. iv
List of figures ............................................................................................ vi

Chapter 1  Introduction ............................................................................. 1
  1.1 Scintillation-based neutron monitors .................................................. 1
  1.2 Pulse shape discrimination ................................................................. 5
  1.3 Motivation ............................................................................................. 6
  1.4 Thesis outline ....................................................................................... 8

Chapter 2  Theory ....................................................................................... 10
  2.1 Introduction .......................................................................................... 10
  2.2 Interaction of radiation with materials ............................................... 11
    2.2.1 Charged particle ............................................................................... 11
    2.2.2 Photons ............................................................................................. 15
    2.2.3 Fast neutrons ..................................................................................... 21
    2.2.4 Thermal neutrons ............................................................................... 28
  2.3 Scintillation light mechanisms ............................................................. 33
  2.4 Scintillator response ............................................................................. 37
    2.4.1 Time response .................................................................................... 37
    2.4.2 Light response .................................................................................... 39
  2.5 Properties for neutron detection ......................................................... 43
  2.6 Thermal neutron detection .................................................................. 45
  2.7 Conventional fast neutron detection ................................................... 46
    2.7.1 Proton recoil detectors ....................................................................... 46
    2.7.2 Detection via fast neutron-induced reactions .................................... 47
  2.8 Capture-gated neutron spectroscopy ................................................... 48
  2.9 Neutron dosimetry ................................................................................ 51
  2.10 Pulse shape discrimination algorithms .............................................. 53
    2.10.1 Analogue techniques ........................................................................ 53
    2.10.2 Digital approach ............................................................................... 58
  2.11 Summary ............................................................................................. 62

Chapter 3  Digital pulse shape discrimination in organic scintillators ...... 64
  3.1 Introduction .......................................................................................... 64
  3.2 Detector assembling and apparatus ...................................................... 64
  3.3 Photomultiplier tube performance ....................................................... 67
  3.4 The neutron source and apparatus ....................................................... 69
  3.5 Circuit description ................................................................................ 71
  3.6 Acqiris waveform digitiser .................................................................... 72
  3.7 Energy calibration ................................................................................ 75
    3.7.1 Description of the calibration technique ........................................... 75
3.7.2 Calibration data .................................................................................................... 76
3.8 Spectral performance ............................................................................................... 80
  3.8.1 Analogue versus digital spectra ........................................................................... 80
  3.8.2 Mixed radiation field ......................................................................................... 82
3.9 Pulse shape discrimination data ............................................................................. 84
  3.9.1 Digital Algorithm ............................................................................................... 84
  3.9.2 The two-dimensional plot of rise time versus energy ........................................ 85
  3.9.3 Performance of the digital PSD algorithm ......................................................... 90
  3.9.4 Tests with no preamplifier ................................................................................. 93
3.10 Discussion .............................................................................................................. 94

Chapter 4 Capture-gated neutron detection ............................................................. 95
  4.1 Introduction ............................................................................................................ 95
  4.2 Circuits description ............................................................................................... 96
  4.3 Capture-gated double pulse sequence data ............................................................ 97
  4.4 Operational characteristics ................................................................................. 98
    4.4.1 SCA adjustment ................................................................................................. 98
    4.4.2 TAC Linearity .................................................................................................... 101
    4.4.3 Saturation of TFA signal ................................................................................... 102
  4.5 Small BC523A data ............................................................................................... 104
    4.5.1 Optimizing the TAC spectra .............................................................................. 104
    4.5.2 Mean capture time ............................................................................................. 107
    4.5.3 Comparison with BC501A detector ................................................................... 108
  4.6 Large BC523A data ............................................................................................... 109
    4.6.1 Optimising TAC spectra .................................................................................... 109
    4.6.2 Mean capture time ............................................................................................. 111
    4.6.3 Digital fast neutron amplitude spectra ............................................................... 112
    4.6.4 Digital spectra due to gated-TAC output ........................................................... 115
  4.7 Coincidence with gated-BGO signal ..................................................................... 117
  4.8 Simulation data ...................................................................................................... 122
  4.9 Discussion .............................................................................................................. 126

Chapter 5 Conclusion .................................................................................................. 128

Bibliography ............................................................................................................... 130

Appendices ............................................................................................................... 134
  A.1 Calculation of scintillation efficiency using XCOM ............................................ 134
  A.2 Monte Carlo simulation data using MCNP-4C .............................................. 135
List of figures

Figure 1-1 A schematic of BC454/BGO detector (Feldman, Barraclough et al. 1999) used to detect the 478 keV γ-ray produced from the $^{10}$B(n, α)$^7$Li reaction. Also shown the neutron (upper left) undergoes a series of scattering (n,p) events. 4

Figure 1-2 The ambient dose equivalent H*(10)/4 derived from ICRU Publication 60 (Siebert and Schuhmacher 1995) as a function of incident neutron energy. 7

Figure 2-1 The basic electron interactions, showing (a) Excitation process at which an orbital electron is excited then returns to its orbit by emission of a photon, (b) Ionisation process at which an orbital electron is ejected from the atom, (c) Bremsstrahlung production as a result of a de-accelerated electron, and (d) Characteristic radiation produced by the de-excitation of an atomic electron. 13

Figure 2-2 Plot of range x density versus energy for electrons in Si and NaI (Mukoyama 1967). Experimentally it is observed that the thickness of absorber in g/cm$^2$ doesn’t change with nature of absorber. 14

Figure 2-3 Relative importance of the major photon interactions as a function of photon energy and absorber atomic number (Evans 1955). Where $\sigma$, $\tau$, and $\kappa$ are the cross sections for Compton scattering, photoelectric, and pair production interactions respectively. 16

Figure 2-4 A schematic of the Compton scattering interaction 17

Figure 2-5 A schematic of energy spectrum recorded by a scintillation detector for photons interacting by photoelectric absorption and Compton scattering. 19

Figure 2-6 Fast neutron elastic scattering. 22

Figure 2-7 The differential scattering cross section of $^4$He at neutron energy of 5.54 MeV. Also shown the angles in the two coordinate systems $\Theta$ and $\Theta'$ and the corresponding energies (in MeV) of the recoiled helium nucleus in the laboratory system (Knoll 2000). 24

Figure 2-8 The elastic scattering cross section for $^1$H, $^3$H, and $^4$He (left). For comparison, the elastic scattering cross section is also shown for $^4$He and $^{12}$C (right), which have lower cross section values at low neutron energies, but shows a resonance at higher neutron energies as indicated in the plot. 26

Figure 2-9 The cross section for neutron-induced interactions of interest in neutron detection. The thermal neutron cross section values falls off with a 1/ν energy dependence for $E<$1 keV but begins to show resonance above 100 keV (Krane 1988). 30

Figure 2-10 Band structure for an inorganic scintillator. 34

Figure 2-11 Energy levels of an organic molecule with π-electron structure (Birks 1964). 35

Figure 2-12 A schematic showing the sum of the two components (fast and slow) in a scintillator. 38

Figure 2-13 The time dependence of scintillation pulses in stilbene (Bollinger and Thomas 1961). 39

Figure 2-14 Scintillation light yield for (NE 102) when excited by electrons and protons (Craun and Smith 1970). The data are fit by curves from Equation 2-42 for one parameter and from Equation 2-47 for two parameters. 40

Figure 2-15 The light output expressed in equivalent electron energy deposition versus proton energy for liquid scintillator NE213 (Maier and Nitschke 1968). The gradient of the line gives $\alpha$ to $\beta$ ratio. 42

Figure 2-16 The ideal response function, a rectangular proton recoil spectrum (left), where $dN/dE$ is constant. Also shown the distorted rectangular shape (right) due to nonlinear response of organic scintillator. 47

Figure 2-17 Principle of the capture gated neutron spectrometer using boron loaded liquid scintillator. Showing, an escaped neutron after a single (a) or multiple scattering (b) is generating a proton recoil pulse in few ns. Also shown, captured neutrons in $^{10}$B after losing all their kinetic energy via scattering process (c), (d). In capture gated neutron spectroscopy, only signals resulting from (c) and (d) are filtered and detected. 48

Figure 2-18 A schematic showing the double-pulse sequence expected from a capture-gated neutron spectrometer when the incident fast neutron is thermalized and captured. 49

Figure 2-19 Schematics of a voltage pulse from a scintillation detector at short time constant ($\tau >> RC$) (a) and large time constant ($\tau << RC$) (b) 55

Figure 2-20 Definition of the figure of merit FOM for the PSD applications. 57
Figure 2-21. Shape of a voltage signal from a fast scintillator represented by: (a) The actual analogue waveform to be sampled, (b) digitised waveform at low sampling rate and (c) digitised waveform at higher sampling rate.

Figure 2-22. The effect of sampling on input signal: (a) original input sine wave with frequency $f_a$, (b) Sampling at $f_s = 2f_a$, (c) Sampling at $f_s < 2f_a$ and (d) Sampling at $f_s >> 2f_a$ that gives a better representation.

Figure 2-23. A block diagram of a 3-bit flash ADC.

Figure 3-1. The large BC523A (left) compared to the small BC523A (right), with volume ratio of ~ 7:1.

Figure 3-2. A schematic illustrating the new design of the BC523A/BGO scintillator.

Figure 3-3. The spectral sensitivity (QE ~ 28%) of a photocathode used with the 52mm photomultiplier tube type 9266B. Data in the plot was taken from the supplier specification sheet (ElectronTubes).

Figure 3-4. The optimum bias voltage (+900 V) for the photomultiplier connected to the BGO.

Figure 3-5. The transmission curve of the 3mm thick window glass, indicating that the visible light is flat and reaches up to 80% at BC523A detector typical emission wavelength values (~ 425 nm).

Figure 3-6. A schematic of the tapered voltage divider type C647.

Figure 3-7. The energy distribution of Am-Be source showing the nuclear reactions that produce the neutron in the source, data in plot were previously reported (Geiger and Van Der Zwan 1975).

Figure 3-8. A schematic of the neutron source contained within a water tank. An air filled adjustable tube is used to vary the proportion of fast neutrons incident on the detector.

Figure 3-9. A block diagram of the digital system used to test the PSD properties of BC523A.

Figure 3-10. Typical rise time of an integrated pulse from BC523A irradiated by Na-22 gamma ray source. The measured 10-90% rise time of this pulse is 28.5 ns.

Figure 3-11. Typical integrated pulse from the preamplifier (upper) and a current pulse from the photomultiplier tube anode (lower) produced from 59 keV gamma rays from $^{241}$Am. The system gain is different in each case.

Figure 3-12. Co-60 energy spectrum using the digital pulse processing system connected to an HPGe detector.

Figure 3-13. Co-60 energy spectrum using the analogue pulse processing system connected to an HPGe detector.

Figure 3-14. The calibration data for analogue detection system connected to the small BC523A, using compton edges of the Na-22 and the Ba-133 sources. For Am-241 and Tb, the photopeak energy was taken.

Figure 3-15. The calibration data for BC501A at high gain setting, using photopeaks from two X-ray sources and one gamma ray source. The shown line is the best fit to the data.

Figure 3-16. The calibration data of BC501A at low gain setting, using Compton edges from three gamma ray sources. The shown line is the best fit to the data.

Figure 3-17. Energy spectrum of Tb source using an 8-bit digital pulse processing system connected to BC523A detector.

Figure 3-18. Energy spectrum of Tb source using a 12-bit analogue MCA connected to BC523A detector.

Figure 3-19. X-ray and gamma ray spectra detected by BC501A detector, showing broad photopeaks obtained with three sources from (a) a mixture of $K_a$ and $K_b$ lines in Ba, (b) a mixture of $K_a$ and $K_b$ lines in Tb, and (c) $^{241}$Am gamma ray.

Figure 3-20. Gamma ray spectra showing Compton edges that are indicated by energies in KeV and corresponding channel number from three sources (a) $^{133}$Ba, (b) $^{137}$Cs, and (c) $^{60}$Co.

Figure 3-21. Energy spectrum obtained from BC523A detector irradiated with Am-Be source using the digital pulse processing system.

Figure 3-22. Energy spectrum obtained from BC523A detector irradiated with Am-Be source using the analogue pulse processing system.

Figure 3-23. Digitised pulses from BC523A due to (upper) a gamma ray source, and (lower) a fast neutron. The marker lines indicate the 10-90% rise time interval.

Figure 3-24. Rise time versus pulse height plot at low gain setting showing fast n/$\gamma$ PSD from BC523A detector.

Figure 3-25. Rise time versus pulse height plot at low gain setting showing fast n/$\gamma$-rays PSD from BC501A detector.

Figure 3-26. Rise time versus pulse height plot at low gain setting from BC408 detector, demonstrating the lack of PSD from this material.
Figure 3-27 Rise time versus pulse height plot at high gain setting showing n/γ PSD from BC523A, but with poor capture n/γ PSD, where the 10B thermal neutron capture events is clearly visible, smeared towards longer rise times.

Figure 3-28 Rise time versus pulse height plot at high gain setting showing n/γ PSD from BC501A detector.

Figure 3-29 Rise time versus pulse height plot at high gain setting from BC408 detector.

Figure 3-30 Rise time versus pulse height plot at low gain setting from large volume BC523A detector, demonstrating the poor n/γ discrimination due to oxygen-induced quenching.

Figure 3-31 Rise time spectra projected from the data in Figure 3-24. The PSD FOM in each case is (a) 1.0 at low energy and (b) 1.2 at high energy.

Figure 3-32 Rise-time spectra projected from the data in Figure 3-25. The PSD FOM in each case is (a) 1.4 at low energy and (b) 1.5 at high energy.

Figure 3-33 Rise-time spectra projected from the data in Figure 3-28. The PSD FOM in each case is (a) 1.4 at low energy and (b) 1.4 at high energy.

Figure 3-34 Rise time (derived from time-over-threshold described in Table 2-7) versus pulse height plot at low gain setting from BC501A with no preamplifier connected (current pulses).

Figure 4-1 The block diagram of capture-gated neutron detection circuit using the small BC523A cell.

Figure 4-2 The block diagram of the modified Capture-gated neutron spectrometer, using the large volume BC523A cell and coincident BGO detector.

Figure 4-3 Two typical double-pulse capture-gated neutron sequences (lower traces) from the low gain TFA signal, captured by a digital oscilloscope at long (left) and short (right) time differences, with the TAC trigger pulse also shown (upper trace). The two images show different neutron capture pulse heights due to different scintillation detector used, where the small BC523A cell and large BC523A cell were used to produce the images in the left and right respectively.

Figure 4-4 The SCA calibration circuit.

Figure 4-5 Effect of the SCA in gating the capture peak. The signal was taken from the high gain TFA2, using the small BC523A cell.

Figure 4-6 Setting the scatter SCA1 for the low gain TFA1, using small volume BC523A cell.

Figure 4-7 Timing measurement circuit.

Figure 4-8 Timing measurements calibration curve (TAC linearity) over 2 μs range using the large volume BC523A cell. Also shown the TAC spectrum using an MCA.

Figure 4-9 Typical double pulses with undershoot and overshoot.

Figure 4-10 The effects of undershoot and overshoot on a saturated high gain (250x) TFA signal.

Figure 4-11 The figure of merit (FOM = A/B).

Figure 4-12 The time difference distribution of the double pulse events.

Figure 4-13 The distribution of the time differences between the first and the second pulse of the double event after subtraction of chance coincidence background events, showing the mean lifetime of the neutrons in BC523A before capture by 10B.

Figure 4-14 Comparison between the time difference distribution obtained using small BC523A (upper) and BC501A (lower).

Figure 4-15 TAC spectra at different SCA settings.

Figure 4-16 The time difference distribution of the double pulse events.

Figure 4-17 The distribution of the time differences between the first and the second pulse of the double event after subtraction of chance coincidence background events in the large BC523A cell. The mean neutron capture lifetime is calculated by linear regression of this data (Jastaniah and Sellin 2003).

Figure 4-18 The pulse height distribution of fast neutrons triggered by the selected window at the true coincidence region on the TAC spectrum. The detailed arrangement of each case is described in Table 4-5.

Figure 4-19 Energy spectrum from TFA signal at low gain setting.

Figure 4-20 Typical examples demonstrating the effect of setting the additional SCA on time difference spectrum, where gated-TAC output due to small (a), medium (b), and large (c) SCA widows.

Figure 4-21 Energy spectra from the digitiser at different SCA settings.

Figure 4-22 Gamma ray calibration curve of BGO detector, where photopeaks are shown for those sources.

Figure 4-23 Spectra due to several gamma ray sources detected by BGO, showing photopeak energies.
Figure 4-24  Spectrum due to Am-Be source in the water tank detected by the BGO. Showing (a) the 478 keV gamma ray from neutron capture in boron, (b) the 2.22 MeV gamma ray from n-p capture, and (c) another higher energy gamma expected to be from carbon interactions.

Figure 4-25  The two input signals (TAC + BGO) in coincidence. To ensure input signals are within the output coincidence window, the output of the coincidence unit triggered inputs.

Figure 4-26  Energy spectra with two coincidence requirements (1) + (2)

Figure 4-27  The energy distribution of proton recoil and gamma ray events incident on (a) the unloaded liquid scintillator, (b) the large BC523A detector, and (c) the small BC523A detector, where the number of events in the large volume BC523A scintillators is higher by a factor of 3 over the small volume BC523A cell.

Figure 4-28  The distribution of gamma rays produced from the Am-Be source interactions with materials such as water and scintillators.
Chapter 1  Introduction

1.1  Scintillation-based neutron monitors

Scintillator materials can be divided according to whether the scintillator is a liquid organic, solid organic (plastic), or inorganic material. The research that began in the 1950’s has led to the development of liquid and plastic organic materials (Kallmann 1950). These scintillators showed superior properties in terms of their shorter scintillation decay time (few ns) compared to that of sodium iodide (230 ns), and are therefore very useful in timing measurements.

The majority of scintillation-based neutron monitors use methods introduced before the 1960’s such as proton recoil spectrometers for fast neutron detection. Despite many attempts to develop a variety of alternative types of neutron detectors, organic scintillators remain in widespread use (Brooks and Klein 2002). For example, fast neutrons are normally detected via proton recoil signals produced by neutron scattering events in hydrocarbon scintillator materials such as liquid or plastic scintillators. These are the material of choice for high energy neutron detection e.g. from 30 MeV to 150 MeV (Buffler, Brooks et al. 2002). Neutron recoil spectrometers based on proportional counters are also used, although the incident neutron energy is limited to a few MeV beyond which proton escapes (wall effect) will occur (Pichenot, Guldbakke et al. 2002).

Existing neutron detection technology (e.g. proton recoil spectrometers) enables the measurement of fluence spectra (and consequently dose) for low energy neutron (e.g. $E_n = 0.5$ MeV to $E_n = 1$ MeV) sources such as $^{252}$Cf, but are not suitable to determine the dose with high accuracy for fast neutron sources such as $^{241}$Am($\alpha$,n)Be (e.g. $E_n$ up to 14 MeV). These spectrometers face difficulties in determining neutron fields at high-energy e.g. accelerator facilities, requiring multiple measurements with different detectors. Without knowledge of
fast neutron spectra, health physicists cannot calibrate their radiation protection instruments and dosimeters, so resulting in incorrect evaluation of the dose received by the personnel.

Some work has been reported for the use of inorganic scintillators in neutron detection e.g. (Bartle and Haight 1999), but liquid and plastic scintillators continue to be the materials of choice, mainly due to their good sensitivity to fast neutrons and gamma rays. Organic materials can also be adapted to detect thermal neutrons by the addition of \(^{6}\text{Li}\) or \(^{10}\text{B}\) (Knoll 2000). The process of loading the scintillator may induce quenching which degrades the light yield and the decay characteristics of the scintillator (Koike and Yamamoto 1970) and (Koike 1971), yet it is very important for neutron absorption e.g. the useful \(^{10}\text{B}(n,\alpha)^{7}\text{Li}\) reaction that is usually applied to slow neutron detection (Chou and Horng 1993) due to the high thermal neutron capture cross section of \(^{10}\text{B}\) (3840 barn). Boron loaded liquid scintillator (BC523 with a \(^{10}\text{B}\) content of 1%) is usually used for slow neutron detection but was also used as part of a full-energy neutron spectroscopy system (Aoyama, Honda et al. 1993), and has provided high gamma ray background rejection without using a gamma ray shield. Compared to the use of a boron tri-fluoride (BF\(_3\)) proportional counter for thermal neutron detection, the size of a BC523 cell can be reduced by an order of magnitude for comparable slow neutron detection efficiency.

Boron loaded liquid scintillator (BC523A) is the enriched type of BC523 (with a \(^{10}\text{B}\) content of 5%). The presence of a thermalization material (hydrogen) and a high concentration of \(^{10}\text{B}\) in BC523A produce a short mean neutron capture time of \(\sim 0.5\) \(\mu\text{s}\) as reported previously (Yen, Bowman et al. 2000). This compares to a mean capture time of the order of \(\sim 2.2\) \(\mu\text{s}\) in the boron loaded plastic BC454 which contains only natural boron (\(^{10}\text{B}\) content of \(\sim 1\)% in polyvinyltoluene-based material) (Feldman 1991). The interaction of thermalized neutrons with BC523A is dominated by neutron capture with \(^{10}\text{B}\) that produces \(^{7}\text{Li}\) and an alpha particle. Two reactions are possible, the first produces \(^{7}\text{Li}\) in the ground state, and the second leaves the nucleus in an excited state (\(^{7}\text{Li}^*\)). The latter nucleus returns to the ground state by emitting a gamma ray of 478 keV in coincidence with the charged particles. The reactions are summarised as follows:

\[
\begin{align*}
94\% \quad & ^7\text{Li}^* + \alpha + \gamma \quad (Q\text{-value} = 2.31\text{ MeV}, \ E_\gamma = 478\text{ keV}) \\
6\% \quad & ^7\text{Li} + \alpha \quad (Q\text{-value} = 2.79\text{ MeV})
\end{align*}
\]
Consequently, the pulse height spectrum produced from thermal neutron interactions in BC523A shows a characteristic broad peak, corresponding to the simultaneous detection of the $^7$Li and $\alpha$ particle. The total energy of each thermal neutron induced event can be either 2.31 MeV when the lithium decays to an excited state or 2.79 MeV when the lithium decays to the ground state. The two energies produce a single unresolved 'neutron capture' peak at a low energy in the pulse height spectrum, typically at about 60 keV electron equivalent (keVee) as reported (Aoyama, Honda et al. 1993), and is due to the significantly reduced light output of the scintillator to charged particles (Birks 1964).

Fast neutron detection is generally very difficult in contaminated fields with gamma rays because gamma ray events will contaminate the neutron energy spectra. Therefore, neutron spectrometers used for characterisation of such fields should either contain a scintillator that is able to discriminate between neutron and gamma ray events (Klein and Neumann 2002), or be gamma ray insensitive. A boron loaded plastic scintillation detector (BC454) was originally designed for purposes of neutron spectroscopy, using the novel 'capture-gated' technique that was first introduced by Drake and Feldman (1986). This method was subsequently reported in more detail by Feldman (1991). The basic concept of this technique is to select fast neutron events that are completely moderated within the detector and then captured by $^10$B. These 'full absorption' neutron events produce a characteristic double-pulse signature. The first signal from this pair of events corresponds to multiple (n,p) collisions in the plastic that moderate the incoming fast neutrons to thermal and epithermal energies, and the second signal corresponds to the neutron capture by the $^10$B(n,$\alpha$)$^7$Li reaction. The initial application for this fast-neutron monitor (known as capture-gated neutron spectrometer) was for characterisations of neutron fluence in space. Studies for other possible applications of the technique include; a neutron coincidence spectrometer for neutron dosimetry (Czirr and Jensen 1994) and the design of a compact fast neutron coincidence counter using BC454 (Miller, Byrd et al. 1997). New materials are currently under investigation for use with capture-gated neutron spectroscopy. An inorganic scintillator compound (lithium gadolinium borate) was incorporated in an organic scintillator (plastic scintillator) to create a fast neutron dosimeter so as to provide the dose rate to high accuracy (Czirr, Merrill et al. 2002). The performance and characteristics of the scintillator in terms of its response to neutrons and gamma rays are described (Czirr, MacGillivray et al. 1999). However, the response of such multi-element compounds is still not well defined. The possibility to create a total energy
absorption neutron spectrometer based on recoil protons using lithium-loaded liquid scintillator was also discussed (Abdurashitov, Gavrin et al. 2002). Neutron capture by the $^6\text{Li}(n,\alpha)$ gives reaction products with energies that are relatively higher than the energies of the daughters nuclei produced by $^{10}\text{B}(n,\alpha)^7\text{Li}$ reaction, but the thermal neutron capture cross section of $^6\text{Li}$ (940 barn) is significantly lower than $^{10}\text{B}$.

Further development in the capture-gated neutron spectrometer involved the combination of two scintillation detectors (phoswich detector), as described by some authors e.g. (Miller, Biddle et al. 1999) and (Feldman, Barraclough et al. 1999), BC454 coupled to a bismuth germanate (BGO) γ-ray detector is schematically shown in Figure 1-1. In this way, a coincidence between the BC454 neutron-capture reaction products ($\alpha$ and $^7\text{Li}$) and the accompanying γ-ray (478 keV) is allowed. This coincidence was used to identify neutron-capture events. However, the BGO detector is also sensitive to gamma ray background as shown in the upper right of Figure 1-1. Such studies have basically used sophisticated electronics to detect all possible interactions individually through several isolated detection systems then performed subtraction of the resultant spectra to eliminate unwanted signal contributions. Therefore, this limits the use of such spectrometers as a portable field instrument.

![Figure 1-1](image-url)  
**Figure 1-1** A schematic of BC454/BGO detector (Feldman, Barraclough et al. 1999) used to detect the 478 keV γ-ray produced from the $^{10}\text{B}(n,\alpha)^7\text{Li}$ reaction. Also shown the neutron (upper left) undergoes a series of scattering (n,p) events.
In this work, capture-gated neutron detection using BC523A scintillator was investigated, and a fast neutron spectrometer that uses digital pulse processing techniques was developed. Compared to other scintillators (e.g. BC454 and BC523) previously used for capture-gated neutron detection, BC523A scintillator has an advantage of its high $^{10}$B concentration. Consequently, it has a lower chance coincidence rate. The volume of BC523A scintillator used for the developed portable fast neutron monitor was chosen with a considerable reduction in size compared to BC454 scintillator used with previously described spectrometers, it was a factor of ~ 4 smaller than BC454 scintillator used by Feldman (1991) and a factor of ~ 10 smaller than BC454 scintillator used by Miller (1999). A coincidence between BC523A and BGO was also investigated in this work. The BGO signal was gated using a window around the 478 keV $\gamma$-ray, and was used to eliminate the chance coincidence contributions to the recorded true coincidence signal.

1.2 Pulse shape discrimination

Pulse shape discrimination (PSD) against gamma rays is advantageous for neutron detection in mixed fields because the organic scintillation detector response to gamma rays can be comparable to that from fast neutrons. Various analogue PSD techniques were introduced (Brooks 1956) to provide a solution for such problems by analysing the shape of the scintillation detector pulses resulting from different radiation type without the sacrifice of neutron detection efficiency.

PSD methods in scintillators have generally used one of the following three analogue techniques (Ranucci 1995). Firstly, rise time inspection that determines the time at which the integrated light pulse reaches a certain fraction of its maximum amplitude. Secondly, the zero-crossing method, which allows an indirect evaluation of the rise time of the pulse performed by measurement of time for a bipolar signal to cross the baseline. Thirdly, the charge comparison method that measures the integrated portions of the signal in the fast and slow components of the light pulses.

Analogue PSD techniques were used to characterise the PSD capability of liquid scintillators (Ranucci, Goretti et al. 1998). Because it has superior PSD capability, liquid scintillators have been employed in studies for $n/\gamma$ discrimination (Okuda, Yamazaki et al.
1999). The PSD properties of BC523A and the unloaded liquid scintillator NE213 (BC501A) was compared (Chou and Horng 1993), the unloaded had a slightly better PSD performance for n/γ discrimination. Generally, the liquid scintillators show good PSD capability due to its slow decay component dependency on the radiation type and energy. In contrast, plastic scintillators are known to have no PSD capability (Birks 1964). Some attempt to enhance the behaviour of plastic scintillators with regard to PSD capability was reported (Normand, Mouanda et al. 2000).

The discrimination between neutron and gamma ray events by examining the width of pulses or the rise time on event-by-event bases using a digital oscilloscope has recently become feasible e.g. (Skulski and Momayezi 2001). However, for the last decade such work was greatly limited by the low speed of the digitiser. Recently, high-speed ADCs have become available, and so the development of digital PSD techniques in organic scintillators has become possible. For example, the acquisition of signals from liquid scintillation detectors using an ADC with a high sampling rate (~ 1 GS/s) to achieve PSD by use of digital algorithms has recently been investigated by a number of authors e.g. BC523A (Jastaniah and Sellin 2002) and BC501A (Marrone, Cano-Ott et al. 2002).

1.3 Motivation

There is particular interest in the development of neutron detection systems for radiation protection purposes (McDonald, Siebert et al. 2002) e.g. to perform accurate dosimetric determination to comply with evolving ICRP standards (Schraube, Kneschaurek et al. 2002). Until now, in order to make a direct measurement of exposure doses from fast neutrons it has been necessary to use bulky detectors (Zecher, Galonsky et al. 1997) to absorb the total kinetic energy of the neutron. In contrast, portable proton recoil neutron monitors are not accurate in measuring the energy of fast neutrons. Therefore, it is of interest to develop an effective full-energy spectrometer for fast neutrons, which is a compact portable instrument that can take advantage of compact digital pulse processing technology. Such a device offers the ability to directly calculate the ambient dose equivalent from the measured neutron energy spectrum using the derived conversion factor (Siebert and Schuhmacher 1995) from ICRU-60 as shown in Figure 1-2, which is described in details in section 2.9. The use of such conversion factor was also recently discussed (Rasolonjatovo, Shiomi et al. 2002).
In mixed neutrons and gamma rays field, an acquired neutron energy spectrum are usually contaminated due to the coexistence of gamma ray events (Lutkin and McBeth 1973). Since the gamma rays have lower biological effectiveness than the neutrons, this will result in incorrect dose measurement. The contributions from neutrons and gamma rays can be measured separately if pulses from fast neutrons and gamma rays can be discriminated, this was under investigation previously using conventional analogue pulse shape discrimination (PSD) methods e.g (Chou and Horng 1993). Today, the rapid growth of computer performance and storage capability of hard discs stimulated the development of high-speed ADCs which opened the door for PSD using waveform digitisers. Two recent studies may be given for example; (Marrone, Cano-Ott et al. 2002) and (Kornilov, Khriatchkov et al. 2003). The fast digital pulse processing systems they have implemented in such works are capable of capturing the complete pulse in digital form. Subsequently, all pulses features can be analysed digitally (e.g. energy information, pulse duration, pulse shape analyses, rise time and noise reduction). However, such studies have concentrated on complex pulse shape
analysis, typically using linear regression techniques to fit a calculated response function to each pulse. Such techniques are highly computationally intensive and poorly suited for real-time processing in potential field instruments. In this work, the emphasis is to explore digital PSD that uses a simple algorithm, which has minimal computational overhead, and consequently is most suitable for the implementation of fast real-time pulse processing in field instruments. This work developed a digital PSD technique that will have potential applications in portable fast neutron monitors because it allows the extraction of a weak fast neutron flux against a strong gamma ray background.

1.4 Thesis outline

This thesis covers the research carried out at the University of Surrey from April 2000 to April 2003 to develop a capture-gated neutron spectrometer with capability of PSD between neutrons and gamma rays using digital pulse processing.

The research began with evaluating the PSD of a commercial boron loaded liquid scintillator (BC523A) cell using data acquisition techniques based on a high-speed waveform digitiser as described in chapter 3. The performance of this scintillator in terms of its response to neutrons, gamma rays and X-rays was compared with other types of organic scintillator i.e. unloaded liquid (BC501A) and standard plastic (BC408) scintillators, and the data are presented in chapter 3. A brief description of all the relevant theories are reviewed in chapter 2, which includes the interaction of radiation with the detector material, the scintillation light mechanisms, the scintillator properties, theory of the neutrons detection technique employed, and the developed digital PSD algorithms.

The suitability of a digital data acquisition for capture-gated neutron spectroscopy using a small volume BC523A cell (commercially available) was explored using the timing measurement circuitry described in chapter 4. Initial tests were carried out on the digital system connected to the commercial BC523A cell that includes energy calibration and spectral performance as presented in chapter 3. The thesis extends to test a large volume BC523A detector produced in the department of physics for capture-gated neutron spectroscopy as described in chapter 4. The new design comprising BC523A and an inorganic scintillator (BGO) for detecting gamma rays, which results from neutron
interactions, and using the BGO signal in coincidence with the BC523A in the capture-gated neutron detection as described in chapter 4. The effect of increasing the scintillation detector volume was investigated to establish whether the neutron detection efficiency can be improved. This investigation was performed by modelling of neutron and photon transport around the detector volume using Monte Carlo methods to verify the experimental data, and the data are shown in chapter 4.

Conclusions regarding the potential for using the developed fast neutron spectrometer in neutron monitoring and dosimetry is given in chapter 5, where future work is recommended.
Chapter 2 Theory

2.1 Introduction

The characterisation of a scintillation detector in terms of its sensitivity to different types of radiation requires knowledge about the nature of the output pulses from the detector. Pulses from an organic scintillation detector are affected by a number of parameters including the interaction of radiation with the scintillator material (energy transfer and decay mechanism of excited states), the response of the detector (light output and time response), the timing properties of the photomultiplier tube, and the pulse processing system. These topics will be described in detail throughout this chapter.

The major ionising radiation types are either charged (heavy charged particles and electrons) or uncharged (neutrons and photons), leading to fundamental differences in their interaction methods. This chapter will present them briefly, but more detailed reviews of relevant theories can be found in other texts e.g. (Smith 2000). In this chapter, more detail is given to the various types of interactions undergone by neutrons - as unlike charged particles, neutrons interactions involve the nucleus of absorber atoms. There are different neutron interactions e.g. scattering and nuclear reactions that can take place depending on the energy of the neutrons. Introducing two arbitrary neutron types based on their kinetic energy can make a simple classification. Neutrons with energy above the cadmium cut-off energy (> 0.5 eV) are known as fast neutrons, whereas neutrons with energy < 0.5 eV are known as slow or thermal neutrons. The mean thermal energy of neutrons is ~ 0.035eV.
2.2 Interaction of radiation with materials

2.2.1 Charged particle

The scope of this research is not directly aimed at the detection of charged particles, but charged particles are produced as a result of neutron interactions. Therefore, it is important to review the interaction mechanisms of charged particles. The consequences of charged particles interacting with a medium are briefly summarised in Table 2-1.

Table 2-1 Summary of charged particles interactions.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Heavy charged particles</th>
<th>Electrons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interaction process</td>
<td>Via coulomb force between the positive charge of particles and the negative charge of an orbital electron</td>
<td>Via coulomb scattering between the negative charge of electrons and the negative charge of an orbital electron</td>
</tr>
<tr>
<td>Tracks</td>
<td>Straight through the material</td>
<td>Large scattering angles</td>
</tr>
<tr>
<td>Range</td>
<td>Short as described by Bragg curve.</td>
<td>Generally more penetrating but less well defined</td>
</tr>
<tr>
<td>Energy loss process</td>
<td>Loss via ionisation and excitation</td>
<td>Loss via ionisation, excitation and electromagnetic radiation</td>
</tr>
<tr>
<td>Rate of energy loss</td>
<td>High</td>
<td>Low</td>
</tr>
</tbody>
</table>

The maximum energy loss $\Delta E$ for an alpha particle in collision with a single electron can be expressed by:

$$\Delta E = \frac{4E_\alpha m_e}{M_\alpha}$$

Equation 2-1

where $E_\alpha$ is the alpha particle kinetic energy, and $M_\alpha$, $m_e$ are the alpha particle and the electron masses respectively. Comparing the two masses in the above equation, then an alpha particle should have many interactions before it loses all its kinetic energy and comes to a
complete stop. When an alpha particle de-accelerates, its energy loss per unit length is quantified as the linear stopping power $S$ that is governed by the Bethe equation:

$$S = -\frac{dE}{dx} = \frac{4\pi\varepsilon_0 z^2}{m_0 v^2 NB}$$

Equation 2-2

where

$$B = Z \left[ \ln \frac{2m_0 v^2}{I} - \ln \left( 1 - \frac{v^2}{c^2} \right) - \frac{v^2}{c^2} \right]$$

Equation 2-3

In the above equations, $v$ and $e\varepsilon_0$ are the velocity and charge of the primary particle, $N$ and $Z$ are the number density and atomic number of the absorber atom, $e$ is the electronic charge, and $m_0$ is the electron rest mass. The parameter $I$ is the average excitation and ionization potential (experimentally determined for each element). For non-relativistic charged particles ($v \ll c$) as in this research, only the first term in $B$ is significant. Equation 2-2 clearly shows the following relationship:

$$\frac{dE}{dx} \propto \frac{1}{v^2}$$

Equation 2-4

or in other words, the energy loss varies inversely with charged particle energy.

In the case of electrons interacting with an absorbing medium, large scattering angles are possible because the masses of the incident electron and the scattering target electron are the same. Apart from this interaction process, there is another possibility of the incident electron interacting with the nucleus of the absorber atom via Bremsstrahlung resulting in abrupt changes in the electron direction. Because there are two possible interactions, the total linear stopping power for fast electrons can be given by the expression:

$$S = \left( \frac{dE}{dx} \right)_c + \left( \frac{dE}{dx} \right)_r$$

Equation 2-5
where $c$ denotes the collisional term due to ionisation and excitation, and $r$ denotes the radiative term due to energy loss by electromagnetic radiation. The specific energy loss of the two terms typically becomes equal at high energies (e.g. for 100 MeV electrons in water). However, for typical electron energies of interest in this study (secondary electrons from few MeV gamma ray interactions), the contribution from the radiative losses is small compared to the collisional losses. In addition, if the absorber material is of a low atomic number, which is the case for liquid and plastic scintillators, the radiative loss will be insignificant. Figure 2-1 illustrates the main interactions of electrons with matter that are important for radiation detectors, in which two cases (a) and (b) are due to the collisional term, and the other two cases (c) and (d) are due to the radiative term in Equation 2-5.

![Figure 2-1](image.png)

**Figure 2-1**  The basic electron interactions, showing (a) Excitation process at which an orbital electron is excited then returns to its orbit by emission of a photon, (b) Ionisation process at which an orbital electron is ejected from the atom, (c) Bremsstrahlung production as a result of a de-accelerated electron, and (d) Characteristic radiation produced by the de-excitation of an atomic electron.
Due to the lower specific energy loss of electrons compared to alpha particles, the range of electrons in an absorber material is much larger than for charged particles. However the concept of range for electrons is less well defined because the total path length travelled by the electron in the absorber and its maximum penetration depth are different. Usually, the product 'range x density of absorber' is assumed constant for a wide range of materials, at any incident electron energy, as shown in Figure 2-2. This quantity is called the absorber thickness and has a unit of g/cm$^2$.

![Figure 2-2](image)

**Figure 2-2**  Plot of range x density versus energy for electrons in Si and NaI (Mukoyama 1967). Experimentally it is observed that the thickness of absorber in g/cm$^2$ doesn't change with nature of absorber.

The absorption of fast electrons as a function of absorber thickness follows an exponential distribution. Consequently an absorption coefficient $n$ could be defined for electrons:

$$\frac{I}{I_0} = e^{-nt}$$

**Equation 2-6**
where \( I \) and \( I_0 \) are the counting rate with and without the absorber respectively, and \( x \) is the absorber thickness in g/cm\(^2\). Thus, the absorption coefficient \( n \) has a unit of cm\(^2\)/g. Equation 2-6 does not apply to very low energy electrons, which may be rapidly absorbed in a thin layer of material. Electron collisions have large scattering angles, which imply that in addition to absorption, fast electrons can also undergo backscattering by emerging back out of the incident surface. Backscattered electrons will not deposit all their energy into the absorbing material, and so can have a significant effect on the response of an electron energy detector (detection efficiency of electrons is reduced by back scattering out of the scintillator). Backscattering is more probable for an absorber of high atomic number and for low incident electron energy.

### 2.2.2 Photons

There are four major processes by which the photon (a quantum of electromagnetic radiation) might interact as it passes through the detector material. The first interaction process is Rayleigh scattering (elastic scattering) that is due to photon scattering from atomic electrons whose binding energy is considerably higher than the incoming photon energy. This interaction is not useful for detector applications because no energy is transferred to the detector medium. The more useful three interactions for detection purposes are Compton scatter (inelastic scatter), photoelectric absorption, and pair production. The relative importance of these three photon interaction mechanisms as a function of energy and atomic number of the detector material are summarised in Figure 2-3, which shows the loci of equal probability for the three interaction processes.

If the incident photon energy is comparable with the electron binding energy, it is more likely that photoelectron interaction will occur. The photon is absorbed by the atom, generating photoelectrons with a kinetic energy determined by the electron binding energy. For example, the kinetic energy of the photoelectron produced, from the K shell \( E_k \) is given by:

\[
E_k = h\nu - BE_k
\]

Equation 2-7
where $h\nu$, is the incident photon kinetic energy and $BE_k$ is the binding energy of the photoelectron in the K shell. The K shell has typical binding energies ranging from a few keV for low Z materials to tens of keV for high Z materials. The vacancy created due to emission of the photoelectron is immediately filled by another atomic electron, therefore emitting either a characteristic X-ray or an Auger electron. If these radiations are stopped within the detector material, then the detector will record the full energy of the incident photon. Photoelectric absorption is the most desirable photon detection mechanism for semiconductor and inorganic photon detectors, however the photoelectric absorption probability $\sigma_{pe}$ is strongly dependent on the Z material and can be expressed by:

$$\sigma_{pe} \propto Z/E_{\gamma}^{0.55}$$

Equation 2-8

where $n$ is roughly 4. Therefore, Photoelectric absorption has a low probability for low Z materials such as liquid and plastic scintillators.

Figure 2-3  Relative importance of the major photon interactions as a function of photon energy and absorber atomic number (Evans 1955). Where $\sigma$, $\tau$, and $\kappa$ are the cross sections for Compton scattering, photoelectric, and pair production interactions respectively.
In Compton scattering, the photon interacts with an orbiting electron whose binding energy is low (free electron) compared to that of the incident photon. The outgoing photon and the scattered electron conserves the energy and momentum of the incident photon. As a result of the interaction the photon energy is reduced and its direction is changed, and the electron that is considered initially at rest recoils with a kinetic energy $E_e$. The energy of the scattered photon $E'$ is given (Evans 1982) by:

$$E' = \frac{E}{1 + \left( \frac{E}{m_e c^2} \right) (1 - \cos \theta)}$$

Equation 2-9

where $m_e$ is the electron rest mass (0.511 MeV/c$^2$), and $\theta$ is the scattered photon angle as shown in Figure 2-4.

The energy of the scattered electron $E_e$ is given by:

$$E_e = E - E'$$

Equation 2-10
From Equation 2-9, this gives:

\[ E_r = E - \frac{E}{1 + \left( \frac{E}{m_0c^2} \right) (1 - \cos \theta)} \]

Equation 2-11

From the above, two extreme cases of scattering photon can be identified:

1- Small angle scattering (grazing) when \( \theta \approx 0 \) and \( E' = E \). Therefore, minimal photon energy loss is expected. This limiting case is not useful for detection as it produces recoiling electrons with negligible energy.

2- Backscattered events when \( \theta \approx \pi \). Therefore maximum photon energy loss is expected and the electron travels along the direction of the incidence. In this case the scattered photon energy can be given by:

\[ E' = \frac{E}{1 + \left( \frac{2E}{m_0c^2} \right)} \]

Equation 2-12

and the recoil electron energy \( E_r \) is given by:

\[ E_r = E \left[ \frac{\left( \frac{2E}{m_0c^2} \right)}{1 + \left( \frac{2E}{m_0c^2} \right)} \right] \]

Equation 2-13

which represent the maximum electron recoil energy. Compton scattering in a scintillation detector will result in an energy spectrum of a complex form as shown schematically in Figure 2-5, where the Compton edge corresponds to the backscattered events \( \theta \approx \pi \).
In Figure 2-5, the energy gap $E_c$ falls between the Compton edge and the full energy peak, and is given by:

$$E_c = E - E_{r|\theta=x}$$

Equation 2-14

$$E_c = E - E \left[ \frac{2E/m_0c^2}{1 + 2E/m_0c^2} \right]$$

Equation 2-15

$$E_c = E \left[ \frac{1}{1 + 2E/m_0c^2} \right]$$

Equation 2-16
From Equation 2-16, the value of $E_r$ tends to a constant value when $E >> m_e c^2/2$. This value is given by:

$$E_r = \frac{m_e c^2}{2} = 0.256 \text{MeV}$$

Equation 2-17

In low-Z detector materials such as liquid and plastic scintillators, Compton scattering is generally the dominant gamma ray interaction mechanism in preference to photoelectric absorption. Consequently low energy (<100 keV) calibration of liquid and plastic scintillation detectors is often carried out using the spectra of the maximum energy Compton electrons (Cherubini, Moschini et al. 1989), for which it is vital to know the Compton edge energy that corresponds to the maximum recoiled electron energy at $\theta \equiv \pi$ using Equation 2-13. For example the maximum recoil energy of the Compton electron from a $^{22}\text{Na}$ decaying by 1.274 MeV $\gamma$-ray, can be calculated as follows:

$$E_r = 1.274 \left[ \frac{(2(1.274)/0.511)}{1 + (2(1.274)/0.511)} \right] = 1.062 \text{MeV}$$

The fourth interaction process (pair production) takes place in the field of a charged particle, e.g. in the strong coulomb field of the nucleus. The photon is absorbed to produce an electron-positron pair. This interaction only becomes energetically allowed for a photon with energy $E$ greater than twice the electron rest mass of 0.511 MeV ($E > 2m_e c^2 = 1.02 \text{ MeV}$), however the probability of pair production remains very low until the photon energy reaches several MeV. Any excess incident photon energy will appear as the kinetic energy of the electron and positron. The positron annihilates with a surrounding atomic electron to produce a pair of back-to-back annihilation photons, each with energy of 0.511 MeV.
In all the above possible photon interactions with detector material, there is a fraction of photons that are transmitted through the detector material of thickness $x$ without any interaction that can be determined by the attenuation coefficient, expressed by:

$$\frac{I}{I_0} = e^{-\mu x}$$

Equation 2-18

where $I$ and $I_0$ are the transmitted and initial photon intensities respectively, and $\mu$ is the linear attenuation coefficient (m$^{-1}$), defined as the probability per unit path length that a photon will be absorbed. In general, $\mu$ is the reciprocal sum of the linear attenuation coefficients for the different photon interaction processes, and depends on both photon energy and the absorbing material. The mass attenuation coefficient is a more useful quantity defined as $\mu/\rho$ where $\rho$ is the material density.

### 2.2.3 Fast neutrons

The dominant interaction of fast neutrons with matter is elastic scattering. In this process, a neutron will slow down as a result of several collisions with nuclei of the target material. Practically, the amount of energy gained by each scattering nucleus is insufficient for detection individually, but an unresolved set of these scattering events can be measured. For neutrons with non-relativistic kinetic energy ($E_n \ll 939$ MeV), conservation of momentum and energy in the centre-of-mass system gives the following relation for the energy of the recoiling nucleus $E_R$:

$$E_R = \frac{2A}{(1+A)^2} (1 - \cos \Theta) E_n$$

Equation 2-19
where \( A \) is the mass number of the target nucleus, \( E_n \) is the kinetic energy of the incident neutron, and \( \Theta \) is the scattering angle of the neutron in the centre-of-mass system as shown in Figure 2-6.

\[
E_R = \frac{4A}{(1 + A)^2} \cos^2 \theta E_n
\]

Equation 2-20

where \( \theta \) is the scattering angle of the recoil nucleus in the lab system, in which can be defined as a function of \( \Theta \) by the following relation:

\[
\cos \theta = \sqrt{\frac{1 - \cos \Theta}{2}}
\]

Equation 2-21

In Equation 2-20, the target nucleus is originally at rest and its recoil energy depends on the angle \( \theta \). For a head-on-collision of the incident neutron with the target nucleus, the nucleus is recoiled almost in the same direction of the incident neutron (\( \theta=\Theta \)), resulting in the maximum recoil energy \( E_R(\text{max}) \). The other extreme is a grazing angle encounter, where
the neutron is slightly deflected and the recoil is emitted perpendicular to the incident neutron \((\theta=90^\circ)\), resulting in the minimum recoil energy \((E_r=0)\). The maximum fraction of an incident neutron energy that can be transferred to a recoil nucleus in a single elastic scattering process is shown in Table 2-2. Only in collisions with proton \((A=1)\) can the neutron transfer all its energy in a single encounter, and \(E_r(\text{max}) = E_n\).

**Table 2-2** The maximum fractional energy transfer in neutron elastic scattering

<table>
<thead>
<tr>
<th>Target nucleus</th>
<th>(A)</th>
<th>(\frac{E_r(\text{max})}{E_n})</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^1\text{H})</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>(^2\text{H})</td>
<td>2</td>
<td>0.889</td>
</tr>
<tr>
<td>(^4\text{He})</td>
<td>4</td>
<td>0.640</td>
</tr>
<tr>
<td>(^{12}\text{C})</td>
<td>12</td>
<td>0.284</td>
</tr>
</tbody>
</table>

For \(E_n < 10\) MeV, it has been found experimentally that all scattering angles are equally probable (isotropic) in the centre-of-mass system, and there will be a uniform energy distribution of recoil nuclei (a continuum of possible recoil energies between the two extremes from \(E_r=0\) to the \(E_r(\text{max}) = E_n\)). The probability of creating a recoil nucleus \(P(E_r)\) with energy \(E_r\) can be expressed by:

\[
P(E_r) = \frac{(1 + A)^2 \cdot \sigma(\Theta) \cdot \pi}{A \cdot \sigma_s \cdot E_n}
\]

Equation 2-22

where \(\Theta\) is the scattering angle of the neutron in the centre-of-mass coordinate system, \(\sigma(\Theta)\) is the differential scattering cross section in the centre-of-mass system, \(\sigma_s\) is the total scattering cross section integrated over all angles (Knoll 2000). Equation 2-22 implies that the expected shape of the recoil energy continuum is the same as the shape of the differential scattering cross section \(\sigma(\Theta)\) as a function of the centre-of-mass scattering angle of the neutron. This is true for most target nuclei as illustrated in Figure 2-7. The shape of \(\sigma(\Theta)\) tends to be peaked to favour forward and backward scattering.
Because the scattering process is isotropic in the centre-of-mass coordinate system for $E_n < 10 \text{ MeV}$, then $\sigma(\Theta)$ does not change with $\Theta$. This simplified case can not be generalised but it holds for scattering from hydrogen over most of the energy range of interest in this work ($E_n < 10 \text{ MeV}$). The expected proton recoil energy distribution is therefore has a simple rectangular shape extending from zero to the full incident neutron energy. Thus, the response function of a detector based on simple hydrogen scattering should have a simple rectangular shape, and the average proton energy is then equal to half of the incident neutron energy.
The scattering cross section \( \sigma \) is used to calculate the detection efficiency of a device based on recoil protons. The intrinsic efficiency \( \varepsilon \) of a detector with only one species of nuclei present (say Hydrogen) is given by:

\[
\varepsilon = 1 - \exp(-N\sigma_id)
\]

Equation 2-23

where \( N \) is the number density of the target nuclei, \( \sigma_i \) is the scattering cross section for these nuclei, and \( d \) is the incident neutron path length through the detector. However, carbon often appears in combination with hydrogen in proton recoil liquid and plastic hydrocarbon scintillators, and for high neutron energies > 10 MeV the neutron-induced inelastic scattering cross section on carbon becomes the most significant source of uncertainty in the calculated neutron detector efficiency (Cecil, Anderson et al. 1979). Thus the counting efficiency taking into account carbon scattering (neglecting any multiple scattering) is expressed by:

\[
\varepsilon = \frac{N_H\sigma_H}{N_H\sigma_H + N_C\sigma_C} \left\{ 1 - \exp\left[ -(N_H\sigma_H + N_C\sigma_C)d \right] \right\}
\]

Equation 2-24

where the subscripts \( H \) & \( C \) refer to the separate hydrogen and carbon values for the quantities defined previously. Plots of the scattering cross section \( \sigma \) for several materials of interest in fast neutron detection are shown in Figure 2-8. Values of \( \sigma \) deduced from the plot can be used to estimate the intrinsic efficiency of a detector. For example, the intrinsic efficiency of BC523A due to proton recoils from elastic collision of 1 MeV neutrons with \(^1\text{H}\) is calculated using Equation 2-23 to be equal to 63% (for estimation of \( d \), see page 32). However, this efficiency drops by approximately 20% (using Equation 2-24) if the incident neutrons on BC523A has energies that exceed 10 MeV due to the competing carbon scattering cross section at \(~ 10\) MeV, whereas the hydrogen will have a lower cross section at this energy as shown in Figure 2-8.
The elastic scattering cross section for $^1$H, $^2$H, and $^3$He (left). For comparison, the elastic scattering cross section is also shown for $^4$He and $^{12}$C (right), which have lower cross section values at low neutron energies, but shows a resonance at higher neutron energies as indicated in the plot.

The kinetic energy of a neutron after a collision $E_{n}'$ with moderating medium nucleus can be given by the following expression (Gibson 1971):

$$E_{n}' = \frac{1}{2} \{(1 + a) + (1 - a)\cos\Theta\}E_n$$

Equation 2-25

and

$$a = \left[\frac{M - m}{M + m}\right]^2$$

Equation 2-26

were $E_{n}'$ is the kinetic energy of the neutron after collision, $E_n$ is the kinetic energy of the neutron before that collision, $\Theta$ is the scattering angle of the neutron from the nuclei in the centre-of-mass system, $m$ is the mass of the neutron, and $M$ is the mass of the moderating medium nucleus. From Equation 2-25 and Equation 2-26, the minimum possible kinetic energy (at $\Theta = 180^\circ$) of a neutron of mass $m$, after a collision with a nucleus of mass $M$ is thus a fraction of its initial kinetic energy expressed (Lilley 2001) by:

$$E_{n}'(\text{min}) = E_n\left[\frac{M - m}{M + m}\right]^2$$

Equation 2-27
The fractional change in the Kinetic energy during elastic scattering may be measured on a logarithmic scale as follows:

\[
\ln \frac{E_n'}{E_n} = \ln \left[ \frac{(1+a) + (1-a)\cos \Theta}{2} \right]
\]

Equation 2-28

At neutron energies below 10 MeV, where the assumption can be made that the neutron scattering is isotropic in the centre-of-mass, then a logarithmic decrement \(\xi\) can be defined as the mean value of \(-\ln \frac{E_n'}{E_n}\), and is expressed by:

\[
-\ln \frac{E_n'}{E_n} = c \xi = c \left[ 1 + \frac{a \ln a}{1-a} \right]
\]

Equation 2-29

where \(c\) is the number of collisions. Therefore, the average number of collisions (\(\overline{c}\)) needed to reduce the kinetic energy of a fast neutron from \(E_n\) to a typical thermal energy value (\(E_n = 0.025\) eV) is given by the following approximate relationship:

\[
-\ln \left( \frac{E_n}{E_{th}} \right) = \frac{c}{\xi}
\]

Equation 2-30

Equation 2-30 demonstrates the neutron kinetic energy dependency on the average number of collisions necessary for the thermalization of a neutron. Examples may be given to describe typical scenarios in which a neutron of 1 MeV slows down by scattering with elements of different Z (Table 2-3). The first few collisions in each example are responsible for most of the neutron kinetic energy loss. This argument can be verified by assuming the
initial kinetic energy of the neutron to be 10 keV, and performing the same calculations. For example in the $^4\text{He}$ case, the calculated average number of collisions needed to thermalize the 10 keV neutron is 30. When comparing this value with the 41 collisions needed to slow down the neutron from its initial neutron energy of 1 MeV to a typical thermal energy, then only 11 collisions were responsible for kinetic energy loss of 0.99 MeV, whereas 30 collisions are responsible for only 0.01 MeV energy loss.

<table>
<thead>
<tr>
<th>Element</th>
<th>Minimum fraction of energy remaining after collision, $a$</th>
<th>Logarithmic decrement, $\xi$</th>
<th>Mean number of collisions for thermalization, $c$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^1\text{H}$</td>
<td>$\sim 0$</td>
<td>$\sim 1$</td>
<td>18</td>
</tr>
<tr>
<td>$^3\text{He}$</td>
<td>0.1110</td>
<td>0.7256</td>
<td>24</td>
</tr>
<tr>
<td>$^4\text{He}$</td>
<td>0.3569</td>
<td>0.4282</td>
<td>41</td>
</tr>
<tr>
<td>$^{12}\text{C}$</td>
<td>0.7141</td>
<td>0.1589</td>
<td>110</td>
</tr>
</tbody>
</table>

In addition to neutron scattering cross section, there is a low probability of undergoing fast-neutron-induced nuclear reactions, which forms the basis of some fast neutron detectors such as $^6\text{Li}(n,\alpha)$. For higher energy neutrons, inelastic scattering with nuclei is possible. In this case the neutron loses more energy than it would lose in an elastic collision. The recoil nucleus is elevated to an excited state, then de-excites, emitting one or more $\gamma$-ray.

### 2.2.4 Thermal neutrons

Slow neutrons generally interact with detector material via nuclear reactions, but can still interact by weak elastic scattering. Only a very small amount of energy is transferred to the recoil nucleus by elastic scattering of slow neutrons, which is not sufficient for detection. However, this process brings the slow neutrons into thermal equilibrium with the medium with an average energy of $= 0.025$ eV. On the other hand, slow neutrons are capable of producing a large set of neutron-induced nuclear reactions that will create secondary radiations of enough energy to be detected. In order for these reactions to be possible the $Q$-
value of the reaction should have a positive value, because the incident neutron energy is almost zero. The most probable reaction that many materials will have when exposed to a thermal neutron flux is the radiative capture reaction \((n,\gamma)\) reaction. Other useful reactions produce charged particles which can be useful for neutron detector materials e.g \((n,\alpha), (n,p)\). Some thermal neutron-induced nuclear reactions are shown in Table 2-4.

### Table 2-4  
Reactions suitable for slow neutron detection.

<table>
<thead>
<tr>
<th>Reaction type</th>
<th>Daughters</th>
<th>Q-value (MeV)</th>
<th>Thermal neutron cross section (\sigma) (barns)</th>
<th>Daughters energies (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^{10})B((n,\alpha))</td>
<td>(94%:^7) Li(^*) + (\alpha + \gamma) (0.48 MeV) (6%:) (^7)Li + (\alpha)</td>
<td>2.31 (\alpha)</td>
<td>3840</td>
<td>(E_\alpha = 0.840) (E_\gamma = 1.47) (E_\beta = 1.02) (E_\gamma = 1.78)</td>
</tr>
<tr>
<td>(^{6})Li((n,\alpha))</td>
<td>(^2)H, (\alpha)</td>
<td>4.78</td>
<td>940</td>
<td>(E_n = 2.73) (E_\alpha = 2.05)</td>
</tr>
<tr>
<td>(^3)He((n,p))</td>
<td>(^1)H, (p)</td>
<td>0.764</td>
<td>5330</td>
<td>(E_n = 0.19) (E = 0.57)</td>
</tr>
<tr>
<td>(^{157})Gd ((n,\gamma))</td>
<td>(\gamma)-rays and conversion electrons</td>
<td>-</td>
<td>255,000</td>
<td>(E_\gamma = 0.072)</td>
</tr>
</tbody>
</table>

The thermal neutron cross section of \(^{10}\)B\((n,\alpha)\) reaction is large compared to the \(^{6}\)Li\((n,\alpha)\) reaction for up to \(-100\) keV as indicated in Figure 2-9. This is one of the advantages of the \(^{10}\)B\((n,\alpha)\) reaction when used for neutron detection. The boron reaction is also preferable because the \(^{10}\)B natural isotopic abundance is \(-19.8\%\) compared to \(^7\)Li of \(-7.4\%\). The \(^3\)He\((n,p)\) reaction has a relatively higher thermal neutron cross section than \(^{10}\)B\((n,\alpha)\) reaction, but is unfavourable because \(^3\)He is a gas and it has a high cost. The thermal neutron capture cross section for the \(^{157}\)Gd \((n,\gamma)\) reaction is among the highest nuclear cross section found in any material. Natural isotopic abundance of \(^{157}\)Gd is 15.7\%, and neutron absorption in this material results in production of conversion electrons that have found some applications in neutron detection and imaging (Czirr, MacGillivray et al. 1999). However, a problem
associated with using the $^{157}$Gd (n, γ) reaction in neutron detection is the low energy γ-rays released.

![Diagram showing cross sections for neutron-induced interactions](image)

**Figure 2-9** The cross section for neutron-induced interactions of interest in neutron detection. The thermal neutron cross section values fall off with a $1/\nu$ energy dependence for $E<1$ keV but begins to show resonance above 100 keV (Krane 1988).

When the incident neutron has near-zero kinetic energy (i.e. thermal neutron), the sum of the kinetic energy of the products in each of the above reactions is equal to the Q-value of the reaction. The individual energies of the reaction products shown in Table 2-4 are calculated from the conservation of energy and momentum:

$$E_{D1} = \frac{Q M_{D2}}{M_{D1} + M_{D2}}$$

Equation 2-31

$$E_{D2} = \frac{Q M_{D1}}{M_{D1} + M_{D2}}$$

Equation 2-32

where $D1$ and $D2$ are two reaction products with masses $M_{D1}$ and $M_{D2}$, respectively.
The probability of a neutron interacting with $^10$B nuclei in the detector material can be described by the cross section $\sigma$ (a parameter that is specific to each type of interaction mechanism and varies strongly as a function of neutron energy). The macroscopic thermal neutron cross section $\Sigma$ (cm$^{-1}$) given in terms of the cross section $\sigma$ (cm$^2$), can then be expressed by:

$$\Sigma = N\sigma$$

Equation 2-33

where $N$ is the number of target nuclei per unit volume of material, with units of cm$^{-3}$. This equation explains why gas is not so good for thermal neutron detection, since $N$ is lower than for a solid. In general, the probability per unit path length that any type of the two interactions (i.e. elastic scatter and neutron capture) will occur is known as the total macroscopic cross section $\Sigma_{\text{tot}}$, and is equal to the summation of all the cross sections multiplied by the number of target nuclei $N$ per unit volume:

$$\Sigma_{\text{tot}} = \Sigma_s + \Sigma_c$$

Equation 2-34

where $\Sigma_s$ and $\Sigma_c$ are the total macroscopic cross sections of scatter and capture respectively. The macroscopic cross section is used in a similar manner to the linear attenuation coefficient for $\gamma$-rays; thus the number of detected neutrons will decrease exponentially with material thickness. The neutrons mean free path $\lambda$ (the distance travelled in a material before an interaction takes place) can then be given by the expression:

$$\lambda = 1/\Sigma_{\text{tot}}$$

Equation 2-35

Typical $\lambda$ values in BC523A scintillator for fast and thermal neutrons may be calculated using the above set of equations (i.e. Equation 2-33 to Equation 2-35). In the case of fast neutrons for example, the distance travelled by a 1MeV neutron before interaction in BC523A can be estimated given the Hydrogen number density $N_H$ (4.98x10$^{22}$ cm$^{-3}$) from the
supplier (Bicron), and the neutron scattering cross section $\sigma_s$ of $^1\text{H}$ ($4.25 \times 10^{-24}$ cm$^2$) from Figure 2-8 as follows:

$$\Sigma_s = N_\nu \sigma_s = 0.212 \text{ cm}^{-1}$$

$$\Sigma_c = N_{n\nu} \sigma_c \text{ (insignificant due to the low neutron capture cross section at 1 MeV)}$$

$$\Sigma_{sc} = 0.212 \text{ cm}^{-1}$$

$$\lambda = 1/0.212 = 4.7 \text{ cm}$$

Similarly, the distance travelled by a thermal neutron ($E=0.025$ MeV) in BC523A before interaction can be estimated given the $^{10}\text{B}$ number density $N_{n\nu}$ ($0.243 \times 10^{22}$ cm$^{-3}$) from the supplier (Bicron), and the neutron capture cross section $\sigma_c$ of $^{10}\text{B}$ ($3840 \times 10^{-24}$ cm$^2$) from Figure 2-9 as follows:

$$\Sigma_c = N_{n\nu} \sigma_c = 9.33 \text{ cm}^{-1}$$

$$\Sigma_s = N_\nu \sigma_s = \text{ (insignificant due to the low neutron scattering cross section at 0.025 eV)}$$

$$\Sigma_{sc} = 9.33 \text{ cm}^{-1}$$

$$\lambda = 1/9.33 \approx 0.1 \text{ cm}$$

The two examples described above demonstrate the accepted distance travelled by a neutron before any interaction occur in BC523A, which in turn provides useful information about the thickness required in the design of neutron monitors using such material.

The quantity $\Sigma_{sc}$ has the same significance for neutrons as the linear absorption coefficient applied to $\gamma$-rays, which is defined by Equation 2-18. Based on the same analogy, a neutron beam attenuated in a thin film of a high thermal neutron absorption cross section element (e.g. $^{10}\text{B}$ or $^{113}\text{Cd}$) can be expressed by:

$$\frac{I}{I_0} = e^{-\Sigma_{sc} t}$$

Equation 2-36
A useful example that is worth mentioning is to find the sufficient cadmium sheet thickness needed to effectively block thermal neutrons from a source such as Am-Be while allowing fast neutron to pass through the material with almost no interactions, where such material behaviour is very useful in fast neutron detection. Using the above set of equations (i.e. Equation 2-33 to Equation 2-35), the estimated $\Sigma_c$ in $^{115}$Cd (has a very high thermal neutron cross section of 20800 barn) is 962 cm$^{-1}$. This quantity can be substituted in Equation 2-36 to calculate the cadmium sheet thickness sufficient to almost completely stop the thermal neutron flux, which was found to be < 0.5 mm.

2.3 Scintillation light mechanisms

A scintillator is a material capable of emitting visible light with a characteristic spectrum, following the absorption of radiation. The ideal scintillator material properties are:

1. High sensitivity (efficiently converts KE of charged particles into detectable light)
2. Fast response (fast scintillation light decay following excitation by radiation)
3. Linearity (light yield should be proportional to deposited energy over a wide range)
4. Efficient coupling to light sensor (similarity in wavelength to sensor window)
5. High transparency of its own wavelength (low self absorption)

Both inorganic and organic scintillators produce optical photons with wavelengths within or close to the visible region. Each type has a different scintillation light mechanism. Inorganic scintillators e.g. sodium iodide (NaI) have a regular crystalline lattice and the scintillation mechanism depends on the energy states of that lattice. Electrons are held in discrete energy bands, the two highest are called valence and conduction bands. The valence band is usually full and the conduction band is empty (insulators). Incident radiation excites an electron to a higher lying conduction band. After some time (typically a few hundred ns), the electron decays back to the valence band via the emission of photoelectron as shown in Figure 2-10. The energy gap (the difference in energy between the top of the valence band and the bottom of the conduction band) is typically 4 eV for inorganic scintillators (insulator).
To increase the photon emission probability and reduce the self-absorption (scintillation light being absorbed in the scintillator material), impurity activators such as thallium (Tl) and europium (Eu) are sometimes added to the alkali halide crystals e.g. NaI(Tl) and CsI(Tl). Some other inorganic scintillators are self activated e.g. zinc sulphide containing excess zinc, but could also be activated by impurities if silver or copper is added to it. The activator atoms will add extra states between the valence band and conduction band, therefore reducing the size of the energy gap. The inorganic crystal that has the highest probability per unit volume for photoelectric absorption due to its high density of 7.13 g/cm$^3$ is bismuth germanate BGO. However, it has relatively lower light yield than NaI (NaI produces ~ 38,000 Photon/MeV, while BGO have only ~ 8200 Photon/MeV).

On the other hand, organic scintillators produces optical photons from the transition in the energy level structure of an individual molecule and therefore is observed from a given molecular species independent of its physical state. Most organic scintillators have π-electron structure (organic molecules with certain symmetry properties) as illustrated in Figure 2-11.
When molecules of an organic scintillator are irradiated, electrons are excited into any one of the excited states. Singlet states (spin 0) are labelled as \( S_0, S_1, S_2, \ldots \) etc. The energy spacing between \( S_0 \) and \( S_1 \) for an organic scintillator molecules are \( \sim 4 \text{eV} \), but for higher level states, the energy spacing becomes smaller. The states with subscripts with typical energy spacing of \( 0.15 \text{eV} \) denoted by \( S_{00}, S_{01}, \ldots \) etc. At room temperature, molecules have thermal energy \( (0.025 \text{eV}) \) that is well below the energy spacing of \( 0.15 \text{eV} \), hence they only exist in the \( S_0 \) state. The excited higher singlet states de-excite to \( S_0 \) by radiationless internal conversion in typical time of the order of picoseconds. The de-excitation from \( S_{0n} \) to any vibrational state of the \( S_{0n} \) forms the fast scintillation light (prompt fluorescence), which decays exponentially, therefore its intensity \( i \) at a time \( t \) following an excitation can be expressed by:

\[
i = i_0 \exp \left( - \frac{t}{\tau} \right)
\]

Equation 2-37
where \( i_0 \) is the initial fluorescence intensity at time zero and \( \tau \) is the fluorescence decay time for \( S_{10} \) level to the various levels of ground state (few nanoseconds). Equation 2-37 is a simplified expression (i.e. function of the fluorescence decay time \( \tau \) only), which assumes that the luminescent states in an organic molecule populate instantaneously, but it was found (Lynch 1968) that it takes \( \sim 0.5 \) ns to populate the levels from which prompt fluorescence originates. This leads to the more generalized expression:

\[
i(t) = i_0 \left( \exp\left(\frac{-t}{\tau_1}\right) - \exp\left(\frac{-t}{\tau}\right) \right)
\]

Equation 2-38

where \( \tau_1 \) is the time constant describing the population (exponential function) of the optical levels. In another approach, the excitation-decay steps was represented by a gaussian function \( f(t) \) characterised by its standard deviation \( \sigma_{ET} \) (Knoll 2000):

\[
\frac{i(t)}{i_0} = f(t) \exp\left( -\frac{t}{\tau} \right)
\]

Equation 2-39

Where \( f(t) \) is expressed by:

\[
f(t) = \frac{1}{\sqrt{2\pi\sigma_{ET}^2}} \exp\left( -\frac{t^2}{2\sigma_{ET}^2} \right)
\]

Equation 2-40

Experimentally, the rise and fall of the pulse (light output) can be characterised by the FWHM at the resulting light versus time profile. Thus it has become common to specify the performance of fast organic scintillators by their FWHM time rather than the decay time alone. NE102A with 2.4ns decay time has a measured FWHM time of 3.3ns (Bengtson and Moszynski 1974).

A set of triplet states are also shown in Figure 2-11 labelled \( T_1, T_2, \) Etc. and have lifetimes longer than the singlet states, typically ms. Some singlet states can be converted to triplet
states via inter-system crossing, causing delayed fluorescence with non-exponential decay times. The de-excitation from \( T_1 \) to the \( S_0 \) is known as phosphorescence, and causes a delayed component (few milliseconds) to the scintillation light, with optical photons of longer wavelengths compared to the optical photons emitted through the fluorescence light de-excitation process. All the optical photons produced from any of the above de-excitation processes, with exception of the \( S_{10} \) to \( S_{00} \), have less energy than that required for generating excited states, thus organic scintillators have little self-absorption. Since the energy absorbed by the molecule in its excitation process is typically larger than the energy of the \( S_{10} \) to \( S_{00} \) de-excitation, this causes a little overlap (Stock's shift) between the absorption and emission bands.

2.4 Scintillator response

2.4.1 Time response

The de-excitation of an organic scintillator is not always governed by Equation 2-37. Apart from the main scintillation component that decays exponentially with decay time \( \tau \) (typically few ns), there is also a slower emission component that decays exponentially in few 100's of ns. The slow scintillation component has been observed in liquid scintillators (Brooks 1958). The time response of organic scintillators that have a slow component becomes more complex and can be given by two exponential decay components of the form expressed by:

\[
I = A \exp \left( -\frac{t}{\tau_F} \right) + B \exp \left( -\frac{t}{\tau_S} \right)
\]

Equation 2-41

where \( A \) and \( B \) are constants, \( \tau_F \) is the fast component and \( \tau_S \) is the slow component. The ratio of \( A \) to \( B \) varies from one type of material to another but the fast component usually dominates as shown in Figure 2-12.
Most of the observed scintillation light from organics given by Equation 2-37 is due to prompt fluorescence (fast component). The fraction of fluorescence that is also exponentially decaying but appears later in time (slow component) depends on the nature of exciting particle (rate of energy loss $dE/dx$ of the exciting particle) and is greatest for particles with large $dE/dx$. Gamma ray interactions give rise to scattered electrons which have relatively low ionisation density. By contrast, neutrons interacting with protons by elastic scattering will cause much higher ionisation densities. For example, the differences of scintillation pulses observed in stilbene crystal when excited by radiation of different types such as alpha particles, fast neutrons (recoil protons), and gamma rays (fast electrons) can be shown in Figure 2-13. In particular, liquid scintillators e.g. BC501A and BC523A are favoured for PSD because of the relatively large differences in the slow component induced by different radiations. In such scintillators, the relative intensities of the fast and slow components depend on $dE/dx$, hence the overall shape of the scintillation pulses produced by different types of particle differs. This forms a useful feature in liquid scintillation detectors, as it can be employed to distinguish between different types of radiation such as neutrons and gamma rays using the technique of PSD (Brooks 1956). These features are investigated in this study to explore digital pulse shape analysis for neutrons and gamma rays discrimination using boron loaded liquid scintillator.
### 2.4.2 Light response

The light output (prompt and delayed fluorescence) from a scintillator is due to energy lost via radiative transitions. The remainder of the incident energy is dissipated non-radiatively via vibration and heat. Therefore the scintillation efficiency can be defined as the fraction of the incident energy that is converted into light, which depends on the particle type and its energy. For some cases however, the scintillation efficiency is independent of the energy, leading to a linear dependence of the light yield on incident energy.

In both liquid and plastic scintillators, the response of the light output to electrons is linear for particle energies > 125 keV. The response to heavy charged particles such as protons or alpha particles is always less for equivalent energies and is non-linear at much higher incident energies. Figure 2-14 demonstrates the scintillation response of a typical plastic scintillator NE102, where the proton response is always less than the electron response. Figure 2-14 shows that at energies of few hundreds keV, the response to protons is smaller by a factor of 10 compared with light yield of equivalent energy electrons.
The relation that described the light response of organic scintillators is known as Birks' formula (Birks 1964), which assumes a relation between $dL/dx$, the scintillation light output per unit path length and $dE/dx$, the specific energy loss for the charged particle:

$$
\frac{dL}{dx} = \frac{S \frac{dE}{dx}}{1 + kB \frac{dE}{dx}}
$$

Equation 2-42

where $L$ is the scintillation light output, $S$ is the absolute scintillation efficiency without quenching: the fraction of deposited energy converted to fluorescence photons (typically ~ 0.04 of $E$, if fully deposited in an efficient scintillator), $B$ is a proportionality constant and $k$ is the fraction of ionisation density leading to quenching. The product $kB$ is an adjustable parameter that depends on the type of particles and their energies, and is used to fit experimental data for a specific scintillator (Hirschberg, Beckmann et al. 1992). In the

Figure 2-14 Scintillation light yield for (NE 102) when excited by electrons and protons (Craun and Smith 1970). The data are fit by curves from Equation 2-42 for one parameter and from Equation 2-47 for two parameters.
absence of quenching or when excited by fast electrons, \(dE/dx\) is small for sufficiently large values of \(E\) (e.g. 1 MeV electrons have low \(dE/dx\), and hence the individual molecular excitation and ionization density along the path are spaced several molecular distance apart, so no quenching exist), thus Birks formula assumes that the light yield is proportional to energy loss:

\[
\left.\frac{dL}{dx}\right|_e = S \left.\frac{dE}{dx}\right|_e
\]

Equation 2-43

Or the incremental light output per unit energy loss is a constant expressed by:

\[
\left.\frac{dL}{dE}\right|_e = S
\]

Equation 2-44

In this case the light output is linearly related to the initial particle energy \((L = SE)\). For heavier particles (proton, \(\alpha\)-particles) and for electrons with energies below 125 keV, \(dE/dx\) is increased compared with that of fast electrons and it is observed that the differential scintillation efficiency \(dL/dE\) is reduced below \(S\) and that \(L\) increases non-linearly with \(E\). In \(\alpha\)-particles for example, the large \(dE/dx\) value causes saturation along the track and Birks formula becomes:

\[
\left.\frac{dL}{dx}\right|_\alpha = S \left.\frac{dE}{dx}\right|_\alpha
\]

Equation 2-45

Using Equation 2-43 and Equation 2-45, the appropriate value of \(kB\) can be determined:

\[
kB = \left.\frac{dL}{dE}\right|_e \div \left.\frac{dL}{dx}\right|_\alpha
\]

Equation 2-46
In order to closely represent experimental data, another formula of $dL/dx$ has been suggested (Craun and Smith 1970), which introduced an additional fitting parameter, $C$ (only an empirical fitting parameter without any physical meaning):

$$
\frac{dL}{dx} = \frac{S \frac{dE}{dx}}{1 + kB \frac{dE}{dx} + C \left( \frac{dE}{dx} \right)^2}
$$

Equation 2-47

Due to the dependence of the light yield of liquid and plastic scintillator on the particle type, it is useful to replace the absolute light yield by a term called MeV electron equivalent (MeV<sub>ee</sub>). Then, the particle energy required to generate 1 MeV<sub>ee</sub> of light by definition is 1MeV for fast electrons, but is more for heavy charged particles because of their reduced light yield per unit energy. The difference of light output (expressed in equivalent electron energy deposition) for a typical organic scintillator from electrons and protons of the same energy is demonstrated in Figure 2-15, where the energy dependence of the light output is best described as proportional to $E^{0.2}$ for energies less than 5.25 MeV, and linear above (Maier and Nitschke 1968). A parameter known as alpha-to-beta ratio is often used to describe this difference in light output behaviour, but this ratio depends on the energy at which the comparison is made, so no fixed value can be applied over the entire energy range. However, since the light yield for electrons is always higher than that for charged particles of the same energy; therefore the alpha-to-beta ratio is always less than 1.

![Figure 2-15](image)

Figure 2-15 The light output expressed in equivalent electron energy deposition versus proton energy for liquid scintillator NE213 (Maier and Nitschke 1968). The gradient of the line gives $\alpha$ to $\beta$ ratio.
2.5 Properties for neutron detection

Organic scintillators have advantages over inorganic scintillators i.e. a short decay time constant and low density relative to inorganic scintillators. As a category, organic scintillators are generally useful for direct detection of β-particles (fast electrons) and α-particles (positive ions), but are also adaptable to the detection of neutrons and gamma rays. Important properties for some commercial organic scintillation detectors, with emphasis on those suitable for neutron detection, are listed in Table 2-5.

Table 2-5 Properties of some organic scintillators (Bicron).

<table>
<thead>
<tr>
<th>Model &amp; Type</th>
<th>Density g/cm³</th>
<th>H/C Ratio</th>
<th>Light output % to Anthracene</th>
<th>% B by weight</th>
<th>Decay constant of main component (ns)</th>
<th>Wavelength λ (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NE102A Plastic</td>
<td>1.032</td>
<td>1.104</td>
<td>65%</td>
<td>-</td>
<td>2.4</td>
<td>423</td>
</tr>
<tr>
<td>BC454 Plastic</td>
<td>1.026</td>
<td>1.169</td>
<td>48%</td>
<td>1</td>
<td>2.2</td>
<td>425</td>
</tr>
<tr>
<td>BC519 liquid</td>
<td>0.875</td>
<td>1.73</td>
<td>60%</td>
<td>-</td>
<td>4</td>
<td>425</td>
</tr>
<tr>
<td>NE213 (BC501A) liquid</td>
<td>0.874</td>
<td>1.212</td>
<td>78%</td>
<td>-</td>
<td>3.2</td>
<td>425</td>
</tr>
<tr>
<td>BC523 liquid</td>
<td>0.916</td>
<td>1.67</td>
<td>65%</td>
<td>1</td>
<td>3.7</td>
<td>424</td>
</tr>
<tr>
<td>BC523A liquid</td>
<td>0.916</td>
<td>1.67</td>
<td>65%</td>
<td>5%</td>
<td>3.7</td>
<td>424</td>
</tr>
<tr>
<td>Anthracene crystal</td>
<td>1.25</td>
<td>0.715</td>
<td>100%</td>
<td>-</td>
<td>30</td>
<td>447</td>
</tr>
</tbody>
</table>

Anthracene is pure organic crystal with highest scintillation efficiency among the organics. The light output of Anthracene is defined arbitrarily to be 100%, and for comparison NaI is 230% on this scale. Being a crystal, it is difficult to obtain in large sizes. Instead, plastic and liquid scintillator cells are available in many sizes and shapes. Their light output ranges from 48-78 % compared to Anthracene. Boron loading tends to slightly reduce
light output in plastic (Drake and Feldman 1986) and liquid scintillators. For example, the plastic scintillator BC454 has light output of 48% compared to Anthracene, while the unloaded plastic scintillator NE102A has a slightly higher light output of 65% on this scale. Similar comparisons can be deduced from Table 2-5 e.g. in the case of liquid scintillators BC523A (65%) and BC501A (78%).

It is important to underline that liquid scintillators should be encapsulated in an oxygen free cell after being de-oxygenated using an inert gas (Schram 1963). The presence of dissolved oxygen produces contact compounds with the scintillator molecules, causing two effects of reducing both the light yield and the relative amount of light in the slow component of the light pulse (Birks 1964). Consequently, PSD properties of the liquid scintillator become poorer. The effectiveness of de-oxygenation procedures for restoring PSD performance in liquid scintillators are reported (Ranucci, Goretti et al. 1998) for different flushing times (0-60 minutes) using nitrogen gas.

Because of its low Z (an organic scintillator mainly consists of hydrogen, carbon and oxygen), a typical organic scintillator shows no photopeak when irradiated with gamma rays because there is very little photoelectric cross section for γ-rays and high energy X-rays. In BC501A detector for example, its low Z and density (0.874 g/cm³), lead to much lower gamma ray absorption coefficients than inorganic scintillators. Therefore, the photoelectric absorption cross section is small at $E_\gamma > 60$ keV, and Compton scattering is the main gamma ray absorption process. In general, a photopeak can be observed by loading the organic scintillator with lead or tin up to 10% by weight, but this will affect the resolution and decrease light output.

The intrinsic detection efficiency of a scintillator relates the counts in the spectrum to the number of γ-rays incident on the detector, and can be expressed by:

$$\epsilon_i = \frac{\text{Event rate recorded}}{\text{Event rate incident on detector}}$$

Equation 2-48

This efficiency is a basic parameter of the detector and is independent of the source-detector geometry. An example that calculates the intrinsic detection efficiency for different inorganic and organic scintillators as a function of γ-ray energy is given in Appendix A.1. However, Equation 2-48 can also be applied to neutron detection efficiency provided that the spectrum corresponds to neutron-induced events only.
2.6 Thermal neutron detection

There are two important factors when using neutron reactions to produce a thermal neutron detector:

(a) The cross section for the reaction must be large, so that a high efficiency detector of reasonable dimensions can be built.

(b) The higher the Q-value, the greater the energy given to the reaction products, and so large amplitude signals are produced in the detector.

Based on the above, thermal neutron detector often make use of organic scintillation loaded with boron such as boron-loaded scintillators, boron trifluoride BF\textsubscript{3} tube and boron-lined proportional counters. However, there are some disadvantages of gas filled counters, such as the long rise time (typically as much as 3-5 µs) and low detection efficiency for average size tube. The boron-loaded plastic scintillator (BC454) has overcome some of these complications, for example enrichment of boron up to 5\% provides a light yield of 75\% of standard plastic, with reasonable detection efficiency. The drawback of boron-loaded plastic scintillator is its lack of n/\gamma PSD due to quenching of slow light component. In order to achieve the separation between gamma ray and neutron pulses, a boron-loaded liquid scintillator (BC523) can be used in conjunction with PSD techniques. PSD methods, which are generally applicable to liquid scintillators, can be used to reject gamma pulses and uniquely identify those due to neutrons.

Due to the high Q-value of \textsuperscript{6}\textsuperscript{Li}(n, \alpha) reaction (Q = 4.78 MeV), organic scintillation detectors were also loaded with lithium providing energetic reaction products. An advantage of this reaction is that it completely populates the ground state of the daughter nucleus, and the reaction products will receive the same energy for all neutron events. This forms an advantage for thermal neutron detection because the pulse height distribution will have a single peak. A \textsuperscript{6}\textsuperscript{Li}-loaded liquid scintillator to 0.15\% concentration (NE320) is available commercially (Ait-Boubker, Avenier et al. 1989) for use as a thermal neutron detector, which offers good PSD against gamma rays. However, \textsuperscript{6}\textsuperscript{Li}(n, \alpha) reaction has a lower cross section for thermal neutrons (940 barns) compared to \textsuperscript{10}\textsuperscript{B}(n, \alpha) reaction (3840 barns).
2.7 Conventional fast neutron detection

2.7.1 Proton recoil detectors

Fast neutron detection with scintillators is often achieved using elastic collisions with light nuclei (hydrogen, deuterium, and helium), for example by detecting recoiling protons from hydrogen. The Q-value of elastic scattering is zero, therefore the sum of the kinetic energies of the recoil nucleus and the scattered neutron must be equal to that of the incident neutron. The scattering process transfers a portion of the neutron kinetic energy to the target nucleus resulting in a recoil nucleus with an average kinetic energy of half the neutron energy. Therefore, it is possible to detect fast neutrons in the presence of gamma ray and other low-energy background, but discrimination is not easy below a few hundred keV.

In fast neutron interactions, the scattered proton energy depends on the scattering angle as discussed in section 2.2.3. Because all scattering angles are equally probable (isotropic for \( E_n < 10 \text{ MeV} \)) so even for monoenergetic fast neutrons incident on an organic scintillator, the response function is not a single peak as would be expected but rather a rectangular shape distribution ranging from zero to the full neutron energy as shown in Figure 2-16 (left). However, the nonlinear response of organic scintillators distort this ideal rectangular shape distribution into the shape sketched in Figure 2-16 (right). For fast neutrons up to \( \sim 5 \text{ MeV} \), the light output \( H \) in many organic scintillators is approximately proportional to \( E^{0.2} \) as demonstrated by Figure 2-15, and is expressed by:

\[
H = k E^{0.2}
\]

Equation 2-49

where \( k \) is a proportionality constant. Therefore, the distorted pulse height distribution expected from an organic scintillation detector based on proton recoils can be given by the approximate relation:

\[
\frac{dN}{dH} = \frac{dN/dE}{dH/dE} = \text{constant} = \frac{3}{2} k E^{1/2} H^{-1/3}
\]

Equation 2-50

where \( k' \) is a proportionality constant too.
2.7.2 Detection via fast neutron-induced reactions

If a fast neutron is moderated within a detector, the moderating process eliminates all the original energy information of the incident neutron; thus detectors that rely on the slowing down of fast neutrons can not be used for neutron spectroscopy. However, this limitation does not exist if fast neutrons are used to induce a nuclear reaction without the moderation step. The reaction products will then have an overall kinetic energy equal to the incoming neutron kinetic energy plus the Q-value of the reaction. Thus, the neutron energy is simply found by subtracting the Q-value from the overall kinetic energy. On the other hand, the detection process is very fast because the neutron spends no more than a few nanoseconds in the detector, and a single reaction is needed to provide a signal. However, fast neutron-induced reactions have very small cross section as shown in Figure 2-9.

Lithium-loaded scintillators can be used for fast neutron detection based on fast neutron-induced reactions. The cross section for the $^6\text{Li}(n, \alpha)$ reaction ($Q = 4.78 \text{ MeV}$) drops smoothly with increasing neutron energy, but a resonance state appears at a neutron energy of 250 keV for which the cross section has a value of 3-4 barns. In fast neutron spectroscopy using the $^6\text{Li}(n, \alpha)$ reaction, a competing reaction occurs $^6\text{Li}(n, n'd)^4\text{He}$ which has a Q-value energy of -1.47 MeV (reaction becomes energetically possible for $E_n \geq 1.47 \text{ MeV}$) and becomes the dominant neutron-induced reaction at energies above about 2.5MeV. The produced neutron normally escapes, and therefore a continuum of deposited energy should be expected.
2.8 Capture-gated neutron spectroscopy

In principle, to achieve full deposition of the kinetic energy of fast neutrons, the scintillator material can be loaded with a high thermal neutron cross section absorber. Thus, following a series of scattering events the neutron will be captured within the scintillator after thermalisation within the detector. However, in typical sizes of scintillation detectors, fast neutrons will most probably deposit part of their energy as they undergo elastic scattering, then escape as shown in Figure 2-17 (a) and (b), producing a proton recoil pulse in the detector but no capture pulse. Hence, even for monoenergetic neutrons the pulse height spectrum has a broad continuum.

![Figure 2-17](image-url) Principle of the capture-gated neutron spectrometer using boron loaded liquid scintillator. Showing, an escaped neutron after a single (a) or multiple scattering (b) is generating a proton recoil pulse in few ns. Also shown, captured neutrons in $^7$Li after losing all their kinetic energy via scattering process (c), (d). In capture-gated neutron spectroscopy, only signals resulting from (c) and (d) are filtered and detected.
For the special case of neutron moderation followed by capture within the detector, a new type of detector, the full-energy-absorption spectrometer has been developed (Feldman 1991). In this device the probability of moderation and capture of fast neutrons is increased by using an organic scintillator loaded with $^{10}$B or $^7$Li. The neutron undergoes a single or multiple scatter followed by neutron capture in $^{10}$B as shown in Figure 2-17 (c) and (d). The proton recoil pulse is due to the sum of many scatter interactions, which occur so quickly that the individual scatter signals are not resolved. The released charged particles from neutron capture in $^{10}$B are scattered almost back-to-back because the neutron carries no appreciable momentum. The charged particles can easily be detected because their combined energy is equal to the Q-value.

Capture-gated events are selected using a hardware trigger that identifies the recoil and capture pulses occurring within a defined time window. The first pulse of this double-pulse event sequence corresponds to multiple (n,p) collisions in the liquid that moderates the incoming fast neutrons to thermal and epithermal energies. The second pulse corresponds to the $^{10}$B(n,$\alpha$)$^7$Li reaction. These interactions can be illustrated as shown in Figure 2-18.

![Diagram showing double-pulse sequence](image)

**Figure 2-18** A schematic showing the double-pulse sequence expected from a capture-gated neutron spectrometer when the incident fast neutron is thermalized and captured.

Identification using both the measured time between consecutive pulses and the energy deposited in the scintillator in the second interaction (which corresponds to the Q-value of the $^{10}$B capture reaction), then signals a fast neutron that has lost all of its incident energy in the scintillator. The pulse height of the first pulse of the pair then provides a measure of the energy of the incident fast neutron.
The time between the first and second interactions in each double-interaction event is described by the probability distribution for neutron capture:

\[ P(t) = \tau^{-1} \exp(-\frac{t}{\tau}) \]

Equation 2-51

where \( \tau \) is the mean capture life time of the thermal neutron before its absorption by \(^{10}\text{B}\). The cross section \( \sigma \) for the \(^{10}\text{B}(n,\alpha)^{7}\text{Li} \) reaction closely follows a \( 1/\nu \) law for neutron energy < 200 KeV as seen in Figure 2-9. Therefore, the capture lifetime \( \tau \) depends solely on the \(^{10}\text{B} \) concentration in the scintillator material and can be expressed by:

\[ \tau = \left[ N_{^{10}\text{B}} \sigma \nu \right]^{-1} \]

Equation 2-52

where \( N_{^{10}\text{B}} \) is the number density of \(^{10}\text{B} \) nuclei in cm\(^{-3} \), and \( \nu \) is the speed of the thermal neutron (approximately 2.21x10\(^5 \) cm s\(^{-1} \)).

Due to its high concentration of \(^{10}\text{B} \), enriched boron loaded liquid scintillators have a short capture time. Based on a full neutron transport (MCNP) simulation (Briesmeister 2000), the variation of mean capture time, mean capture distance (straight-line) and capture fraction with \(^{10}\text{B} \) concentration has been computed (Wang, Hsu et al. 1999) as shown in Table 2-6. Both the capture time and the fraction are independent of the initial neutron energy, but the capture distance reported was modelled using neutrons with an initial energy of 0.5 keV.

<table>
<thead>
<tr>
<th>(^{10}\text{B} ) (% by weight)</th>
<th>Mean capture time (µs)</th>
<th>Mean capture distance (cm)</th>
<th>Capture fraction in (^{10}\text{B} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>4.7</td>
<td>4.4</td>
<td>0.98</td>
</tr>
<tr>
<td>1.0</td>
<td>2.3</td>
<td>4.0</td>
<td>0.99</td>
</tr>
<tr>
<td>3.0</td>
<td>0.86</td>
<td>3.1</td>
<td>1.0</td>
</tr>
<tr>
<td>5.0</td>
<td>0.62</td>
<td>2.69</td>
<td>1.0</td>
</tr>
</tbody>
</table>
Using a capture-gated spectrometer, the neutron detection efficiency is typically few percent (Brooks and Klein 2002) depending on the neutron energy, and may be affected by a number of parameters including the scintillator volume and the concentration of the capture-element (e.g. boron) that is seeded in the detector.

### 2.9 Neutron dosimetry

The energy absorbed from any type of radiation per unit mass of the absorber material has the units of gray (Gy) that is equal to 1 joule/kilogram. However, this quantity defined as the absorbed dose does not consider the biological effects of radiation on living organisms. The severity of the biological damage created by ionising radiation is directly related to the local rate of energy deposition along the particle track (linear energy transfer LET). Neutrons interacting with matter produce charged particles that are known to have large values of LET, therefore results in greater biological damage than electrons that have a lower value of LET even though the total energy deposited per unit mass may be the same.

For the estimation of the effects of radiation on living organisms, the concept of dose equivalent has been introduced. A unit of dose equivalent is defined as the amount of any type of radiation that, when absorbed in a biological system, results in the same biological effect as one unit of absorbed dose delivered in the form of low-LET (electrons) radiation. The dose equivalent $H$ in units of sievert (Sv) is the product of the absorbed dose $D$ and the quality factor $Q$ that characterises the specific type of radiation:

$$H = DQ$$

Equation 2-53

For fast electrons including those secondary electrons produced from gamma ray and X-ray interactions, LET is low so that $Q$ is unity. This will lead to dose equivalent that is numerically equal to the absorbed dose. Due to their higher values of LET, heavy charged particles including those produced via neutron-induced interactions have a dose equivalent that is larger than the absorbed dose. The quality factor in the case of neutrons-induced charged particles is greater than unity, and varies significantly with neutron energy.
For relatively penetrating radiations such as neutrons and gamma rays, it is convenient to estimate the dose equivalent to exposed personnel from a given fluence of radiation. In terms of the neutron flux, the fluence is the time integral of the flux over the exposure duration. For a monodirectional beam, fluence can be defined as the number of photons or neutrons per unit area, where the area is perpendicular to the direction of the beam. In general, fluence can be defined as:

\[ \Phi = \frac{dN}{dA} \]

Equation 2-54

where \( dN \) is the differential number of gamma ray photons or neutrons that are incident on a sphere with differential cross-section area \( dA \). For a point source, the fluence can be given by the expression:

\[ \Phi = \frac{N}{4\pi d^2} \]

Equation 2-55

where \( N \) is the number of neutrons or photons emitted by the source assuming negligible attenuation in air over small distances, and \( d \) is the distance from the source. In practice, the number of counts recorded on the detector (interpreted in terms of the number of radiation-induced interactions in the detector) can be related to the fluence. A conversion between the fluence and the dose is hence necessary.

All calculations that have been made for the dose absorbed in a physical model of the human body were sensitive to the direction of the incidence of the radiation because of self-shielding and attenuation effects within the body. Following the recommendations (ICRP 1991) of ICRP-60, tissue weighting factors was used to account for differing radiosensitivity of various organs, and the dose equivalent of an individual organ could be combined into an effective dose equivalent \( H_e \) for the overall biological effect of a whole body exposure to the fluence (ANS 1991), as given by:

\[ H_e = h_e \Phi \]

Equation 2-56
where $h_E$ is the fluence-to-dose factor (conversion factor for neutron dosimetry as a function of neutron energy) derived from ICRU Publication 60 (Siebert and Schuhmacher 1995).

Because neutrons are strongly penetrating radiation, the values for $h_E$ are best expressed in terms of ambient dose equivalent $H^*(10)$ at a recommended depth of 10 mm inside the exposed skin divided by the fluence $\phi$. The quantity $H^*(10)/\phi$ are plotted as a function of energy as shown in Figure 1-2, where neutron energies are ranging from 1 keV to more than 10 MeV. If the full energy of an incident neutron on a detector can be measured, then the ambient dose can be directly calculated, and a dosimeter can be built based on an event-by-event measurement.

### 2.10 Pulse shape discrimination algorithms

#### 2.10.1 Analogue techniques

Detectors may be operated in current or pulse counting modes. Pulse mode of operation preserves the amplitude and timing information of each pulse produced by the detector, which is the normal mode of operation in spectrometers. However, in the case where the pulse rate increases, the complexity of the following analysis electronics increases. At very high rate, it is necessary to use a detector in the current counting mode.

The light output of the scintillator is transformed by a photomultiplier tube into an electric current that has the same exponential behaviour given by Equation 2-37. In a pulse mode, normally this current is fed into an $RC$ circuit (connected to a preamplifier that will have a characteristic input resistance $R$ and input capacitance $C$), so this current is integrated over the charge collection time period, reaching maximum voltage amplitude $V_{\text{max}}$ that corresponds to $Q/C$. The voltage signal then decays to zero as the capacitor discharges, with a characteristic time determined by $RC$. In practice, $C$ represents the total capacitance of the detector, connecting cable, and the preamplifier. Consequently, the detection system has an associated time constant $RC$ of the readout circuit (the characteristic time for the detector signal to decay to zero). The time constant $RC$ is kept long enough (typically 5-10 times the scintillator decay time $\tau$) to collect all of the detector charge, but it should also be short to allow fast pulse counting. The effect of the long or short time constants can be schematically shown in Figure 2-19, where the effect of the two opposite cases ($RC \gg \tau$ and $RC \ll \tau$) is
important in determining the scintillator decay time $\tau$. The approximated relations derived (Knoll 2000) for the voltage pulse at short and long time constants of the $RC$ circuit explains how the scintillation decay time $\tau$ is taken from the current and pulse modes. In the case of $RC \gg \tau$ (integrated pulse), the radiation interaction energy is extracted from pulse amplitude and $\tau$ is extracted from pulse rise time. The behaviour of the voltage pulse $V(t)$ in this mode of operation can be represented by the expression:

$$V(t) \equiv \frac{Q}{C} \left( e^{-\frac{t}{\tau}} - e^{-\frac{t}{RC}} \right)$$

Equation 2-57

where $V(t)$ has the pulse shape shown in figure Figure 2-19 (a), this corresponds to the output of an integrating preamplifier, where at short times (i.e. the leading edge), $V(t)$ has the form:

$$V(t) \equiv \frac{Q}{C} \left( 1 - e^{-\frac{t}{\tau}} \right) \quad \text{for} \quad t << RC$$

Equation 2-58

and at longer times (i.e. the tail of the pulse), $V(t)$ has the form:

$$V(t) \equiv \frac{Q}{C} e^{-\frac{t}{RC}} \quad \text{for} \quad t >> RC$$

Equation 2-59

From the two voltage pulses (Equation 2-58 and Equation 2-59), three important properties can be noted:

1. The rise time of the pulse (leading edge) is determined only by the scintillator time constant $\tau$. Fast scintillators such as liquid scintillator have small $\tau$ values.
2. The tail of the pulse decays away at a rate determined by the $RC$ circuit time constant.
3. Provided that the capacitance of the detector remains constant, the signal amplitude $V_{MAX}$ is directly proportional to the energy of the initial radiation interaction.
In the other case where $RC \ll \tau$ (current pulse), very little charge will be integrated on the capacitor, and the output will reflect the temporal output of the detector itself. It follows that, $\tau$ is extracted by the tail of the signal (pulse decay time) that is identical to that of the scintillator light as shown in Figure 2-19 (b), and the leading edge this time is determined by the $RC$ circuit time constant. Thus, the radiation interaction energy can be extracted from pulse integral.

In practice, an approximation to a fit of the leading edge of the integrated pulse shape expressed by the relation Equation 2-57 describing the long time constant (i.e. $RC \gg \tau$) may be given by:

$$RT (ns) = t_{90\%V_H} - t_{10\%V_H}$$

Equation 2-60
where \( t_{90\%V_H} \) and \( t_{10\%V_H} \) is the time at which the pulse reaches 90% and 10% of its height \( V_H \) respectively. This simple algorithm can be used as a PSD technique to perform tests for radiation type identification. The 10-90% rise time algorithm described above can also be extended to a 5-95% rise time algorithm based on the same approximation, where the measured rise time should be a closer measure to the actual amplitude of the leading edge of the pulse. Another simple PSD algorithm based on the same analogy of measuring the rise time of the pulse is the “time over threshold”, which is used with current pulses at the output of a photomultiplier tube directly. Some studies e.g. (Marrone, Cano-Ott et al. 2002) and (Kornilov, Khriatchkov et al. 2003) have concentrated on more complex pulse shape analysis, typically using linear regression techniques to fit a calculated response function to each pulse. Such techniques are highly computationally intensive and poorly suited for real-time processing in potential field instruments. A summary of most popular analogue PSD methods are described in Table 2-7.

Table 2-7 Summary of most popular analogue PSD algorithms.

<table>
<thead>
<tr>
<th>PSD algorithm</th>
<th>Signal used</th>
<th>Description of method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charge integration</td>
<td>Anode signal (current pulse)</td>
<td>The method relies on comparing the charges due to rise and fall times of the PM tube output pulse (integrating it in two different “time windows”, then calculating the ratio between the two components.</td>
</tr>
<tr>
<td>Rise time measurements by leading edge method</td>
<td>1. Anode signal (current pulse)</td>
<td>1. The width “time over a threshold” is measured.</td>
</tr>
<tr>
<td></td>
<td>2. Preamplifier signal (integrated pulse)</td>
<td>2. Measuring the interval between the times at which the pulse reaches 10% and 90% of its maximum amplitude.</td>
</tr>
<tr>
<td>Rise time measurements by zero crossing method</td>
<td>Amplifier signal (shaped bipolar pulse)</td>
<td>Measuring the time interval between the beginning of the each bipolar pulse and the instant it crosses the baseline. This time interval is independent of the pulse amplitude but rather on the pulse shape.</td>
</tr>
</tbody>
</table>

The degree of separation between the neutron and the gamma ray peaks in pulse rise time spectra can be estimated by a widely used method (Winyard, Lutkin et al. 1971). The method
was used to characterise PSD properties of a boron loaded liquid scintillation detector (Wang, Hsu et al. 1999). In this method, a figure of merit (FOM) was defined as:

\[
FOM = \frac{S_{n\gamma}}{F_n + F_\gamma}
\]

Equation 2-61

where \(S_{n\gamma}\) is the separation between the centroid of the neutron peak and the gamma peak in the rise time spectrum, and \(F_n, F_\gamma\) are the full width half maximum values of the two peaks respectively as shown in Figure 2-20. In this schematic model, the unwanted gamma peak can theoretically be 100% separated and thus rejected, in which typical values of FOM corresponding to this case should be > 1. On the other hand, lower FOM values achieved means that the PSD properties are imperfect. The FOM usually ranges from 0, for no PSD, to greater than 2, for excellent PSD. Two factors must be considered when estimating the FOM, the dynamic range of the pulse amplitudes and the count rate, as they will determine the degree of discrimination achieved.

![Figure 2-20](image.png)  
Figure 2-20 Definition of the figure of merit FOM for the PSD applications.
2.10.2 Digital approach

Digital PSD algorithms use digital pulse shape analysis of detector pulses that have been completely digitised. The first part of the digital pulse processing, in which analogue pulses are converted into digital patterns, is known as the sampling process. To illustrate this operation, an example of a voltage pulse from a fast scintillator is shown in Figure 2-21, where (a) shows the shape of the input analogue signal to be sampled, (b) shows the shape of the digitised waveform at low sampling rates missing crucial information at the turning point of the signal and (c) shows the waveform at a higher sampling rates that is closer to the real analogue shape.

![Figure 2-21](image)

**Figure 2-21** Shape of a voltage signal from a fast scintillator represented by: (a) The actual analogue waveform to be sampled, (b) digitised waveform at low sampling rate and (c) digitised waveform at higher sampling rate.

The theorem that defines the minimum frequency required to accurately represent an analogue signal is known as Shannon’s sampling theorem. In order to accurately represent an analogue signal, the minimum sampling frequency $f_s$ (Nyquist frequency) must be equal to or greater than twice the highest frequency component $f_n$ (band width) of the original signal.
The effect of sampling an analogue signal is similar to multiplying the input signal with a series of sine waves of frequency $f_s$ at multiples of the sampling frequency $f_s$ as illustrated in Figure 2-22, where (a) is the sine wave with frequency $f_a$, (b) is the sampling at $f_s = 2f_a$ (Nyquist limit) in which the waveform gives a triangular wave, (c) is the sampling at $f_s < 2f_a$ in which the waveform does not retain any of the characteristics of the sine wave but rather gives a distorted (different frequency) sine wave caused by aliasing effect (Marven and Ewers 1996) and (d) is the sampling at $f_s >> 2f_a$ that gives an accurate representation of the analogue signal.

![Figure 2-22](image)

**Figure 2-22** The effect of sampling on an input signal: (a) original input sine wave with frequency $f_a$, (b) Sampling at $f_s = 2f_a$, (c) Sampling at $f_s < 2f_a$ and (d) Sampling at $f_s >> 2f_a$ that gives a better representation.

In practical design, the basic sampling function is replaced by “sample and hold” circuit that keeps the sample level until the next sample is taken resulting in a staircase waveform. By converting the input analogue signal to this format, it can be interpreted by a digital signal processor (DSP). The sampled values are converted into numbers (quantization operation) by an ADC that provides the necessary means of interfacing between the analogue and digital domains. An analogue signal has an infinite range of levels while a digital signal can take only a finite number of levels. Therefore, the more bits an ADC has, the more accurately the analogue signal is described. An 8-bit ADC will measure the input signal against $2^8$ (256)
digital output levels. Thus, input signal that is varying between 0 and 1 V will have a least significant bit (LSB) correspond to just 3.9 mV for the 8-bit ADC, and 0.24 mV for a 12-bit ADC. The difference between the true analogue input signal and the nearest digital approximation offered by the converter (quantization error) is ±½ LSB, and is a measure of linearity.

A simple and fast digitisation method is possible using the flash (or parallel) type ADC, which is presented by a 3-bit flash ADC shown in Figure 2-23. It consists of a stack of thresholds comparators (3-bit resolution, $2^3 = 8$ comparators) with increasing voltage levels, provided by a resistive voltage divider (the inverting inputs of the comparators are biased progressively in equal steps via a resistor chain). The resistance value $R$ between each comparator is identical. A given analogue input level causes all those comparators whose bias is less to have their output high and all whose bias is greater to have their output low. A sequence of gates encodes the comparator output into the usual binary format while a latch is normally included to hold the conversion state for reading. Consequently, conversion speeds in excess of 500 MHz are possible with this method, but each additional one bit of resolution doubles the required number of comparators. Therefore, an 8-bit flash ADC requires $2^8 = 256$ comparators. In the most modern types of waveform digitisers used in this work, an 8-bit ADC with minimum (1 ns) sampling time was used.

![Figure 2-23 A block diagram of a 3-bit flash ADC.](image)
Data smoothing of the digitised waveform can be carried out by two kinds of filters i.e. analogue and digital, which operate in different ways. Analogue filters use electronic circuits, so that the signal being filtered is an electrical voltage or current, which is the direct analogue of the physical quantity (e.g. anode or preamplifier pulse). In a digital filter however, the filter is a mathematical algorithm applied to the discrete waveform after digitisation. Many examples of digital filters are used such as the simple gain filter, pure delay filter, two-term difference filter, and two-term average filter. The main advantages of digital filtering are that the technique is programmable, stable, and compact.

Digital filtering allows suppressing the bandwidth of the signal in a controlled way in order to remove only unwanted parts of the signal. The computational algorithm (filter) for the smoothing process is a convolution of the experimental data sequence by the filter coefficient. A commonly used algorithm is the moving average, which assumes linear weighting of the input data sequence. The smoothed output data are expressed by:

\[ Y_j = \sum_{k=-N_p}^{N_p} b_k X_{j+k} \]

Equation 2-62

where \( X_j \) is an equally spaced data sequence that is required to be smoothed, \( N_p \) is the number of points either side of the \( k^{th} \) point and \( b_k \) are the weighting factors i.e. the coefficients of the filter. It is the values of these coefficients that determine the characteristics of a particular filter. The total number of filter coefficients is known as the filter width \((2N_p + 1)\). Three sufficient conditions must be satisfied for \( b_k \) to be a smoothing filter. These conditions are:

1. The sum of all the coefficients is equal to 1 \( \left( \sum_{k=-N_p}^{N_p} b_k = 1 \right) \)

2. The coefficients must be symmetrical about the central coefficient \( b_0 \) (e.g. \( b_i = b_{-i} \));

3. The coefficients must have the sequence \( b_0 > b_1 > \ldots > b_{N_p} > 0 \).

Another group of filters having all the above properties comprises the binomial smoothing filter. It has excellent characteristics faster than a least-square polynomial filter in terms of the computational algorithm, and can have better signal-to-noise ratio in both the time and
frequency domains (Marchand and Marmet 1983). The binomial filter \((2N_p + 1)\) coefficients are defined by the binomial coefficient formulae:

\[
b_k = \binom{2N_p}{N_p + k} \quad (k = 0, 1, 2, \ldots, N_p)
\]

Equation 2-63

Using Equation 2-64, for \(N_p = 1\), the sequence that can be obtained is \(1/4, 1/2, 1/4\), and so on for higher values of \(N_p\). For small values coefficients can also be obtained by every other row of the Pascal triangle.

Programs using a further class of filters \((2N_p + 1)\)-point moving average) are very good in noise reduction, where the coefficients are all equal, and can be expressed by:

\[
b[k] = \frac{1}{(2N_p + 1)}
\]

Equation 2-64

The smoothing performance of the filter function is directly related to its width. So as \(N_p\) increases the smoothing action increases, so the filter performance becomes better. But it is crucial to account for computation time in real-time applications.

2.11 Summary

The development of a digital-based fast neutron spectrometer with PSD capability requires knowledge about the generation and behaviour of pulses from a scintillator material and the response of an organic scintillation detector to different radiation types, which are discussed in details. Pulse shapes produced from liquid scintillators have extremely fast decay times, typically < 10 ns for electrons (gamma ray interactions) and 50-100 ns for protons (neutron scatter interactions). Consequently the use of digital PSD relies on fast waveform digitisers with ~1 ns timing resolution. The PSD performance may be characterised by two
computationally-simple digital pulse shape algorithms; (1) the 10-90% pulse rise time, and (2) the pulse time over threshold. The risetime algorithm can be applied to integrated pulses produced from a charge integrating preamplifier, and the time over threshold algorithm can be applied to current pulses produced directly from the PMT anode.

The use of PSD performance in liquid scintillators relies on the presence of long lifetime components of the scintillation light produced by high LET events such as proton recoils due to neutron scatter events. A variety of analogue pulse discrimination techniques have been used to extract good n/γ discrimination. Recently, the availability of high speed waveform digitisers with sampling times of the order of 1ns has made possible the complete digitisation of pulses from liquid scintillators on an event by event basis. The use of 10-90% rise time algorithm, a relatively simple pulse shape algorithms in several liquid and plastic scintillators have been selected in this work due to their minimal computational overhead, which are most suitable for the implementation of fast real-time pulse processing in field instruments.

Digital PSD techniques is useful to capture-gated neutron spectroscopy; because it can separate the neutron-induced events therefore enhance the gamma ray rejection of the system without the sacrifice of the neutron detection efficiency as normally is the case with other neutron spectrometers. Interaction of a fast neutron produces first a moderation pulse consisting of the multiple-scatters of the moderating neutron which are unresolved in a single ‘scatter’ pulse. After a characteristic time τ corresponding to the mean capture lifetime of thermal neutrons, a second ‘capture’ pulse is observed due to the detection of the 7Li and α particles from the capture of the moderated neutron by 10B. The amplitude of the capture pulse is fixed equal to the Q-values of the 10B n-capture reaction. The kinetic energy of the incident fast neutron is obtained, in principal, from the amplitude of the scatter pulse. Therefore the whole body dose may be calculated precisely based on a conversion factor between the neutron energy in MeV and the dose equivalent in Sv.cm².
Chapter 3  Digital pulse shape discrimination in organic scintillators

3.1  Introduction

The experiment described in this chapter explores digital PSD algorithms for neutron and gamma ray spectroscopy using BC523A boron loaded liquid scintillator and compare its performance with other unloaded organic scintillators. In order to investigate the differences in the shapes of the BC523A pulses, a simple digital pulse shape algorithm was implemented that was not computer intensive (10-90% rise time algorithm). A high-speed 8-bit waveform digitiser (WFD) was used. The digitiser had a high bandwidth PCI bus connection to a PC to achieve event-by-event acquisition of complete detector waveforms at reasonable event rates (typically 1 kHz). The PC computer running dedicated data acquisition software performed real-time extraction of event parameters such as energy and rise-time from the acquired waveforms.

This chapter begins by describing the work that has been done to assemble the scintillation detectors, the detector-source arrangement and the energy calibration. The performance measurements of the PSD algorithms in the various scintillator materials are then discussed.

3.2  Detector assembling and apparatus

Two boron loaded liquid scintillator cells (BC523A) are shown in Figure 3-1. The small commercial cell (Bicron) has a volume of ~ 105 cm³, while the other cell was produced in the department with a larger volume of ~ 685 cm³. The atomic composition of the cells includes
Hydrogen at a number density of $4.98 \times 10^{22}$ atoms/cm$^3$ and $^9$B at a number density of $0.243 \times 10^{22}$ atoms/cm$^3$.

![Figure 3-1](image)

**Figure 3-1** The large BC523A (left) compared to the small BC523A (right), with volume ratio of $\sim 7:1$.

The larger cell shown in Figure 3-2 was designed to provide a performance comparison with the smaller commercial cell. In particular, it was of interest to investigate how the energy, PSD and fast neutron detection efficiency characteristics varied with a larger scintillation volume. In addition, the design also included gamma ray spectroscopy using a BGO cell (inorganic crystal made of Bi$_4$Ge$_3$O$_{12}$, with cylindrical shape of height = 52 mm and diameter = 30 mm) that was located in the centre of the liquid scintillator cell as shown in Figure 3-2. In particular, the BGO was used for better identification of neutron absorption event in $^9$B that are sometimes accompanied by the release of the 478 keV gamma ray as described by the $^9$B(n, $\gamma$)$^7$Li interaction shown in Table 2-4.
The liquid scintillator cell was made of 5 mm thick aluminium. The cell has a cylindrical shape of 104 mm in height by 104 mm in diameter, but this diameter was reduced toward the end to match the photomultiplier tube diameter of 52 mm as shown in the right hand side of Figure 3-2 A 52 mm diameter glass window was fitted at this end using a special adhesive called Torrseal (Varian). The use of a special adhesive was recommended by the liquid scintillator producer (Bicron) because liquid scintillator softened (attacking the chemical bonds) ordinary adhesives, consequently leakage and gas exchange occurred. The side of the surface where the adhesive was applied was cleaned and made rough using sodium hydroxide, NaOH at 5% w/w prior to applying the Torrseal adhesive. Taking all safety measures, the liquid scintillator was then poured into the cell though the opening that was sealed afterwards with a screw made of aluminium. The liquid in the cell was de-oxygenated by bubbling pure dried nitrogen, N₂ through the opening. However, the exchange of gases in the solution was surprisingly rapid, and contamination was established with oxygen during a brief period necessary for the handling and sealing of the cell.
3.3 Photomultiplier tube performance

The most important consideration when selecting a photomultiplier tube is to seek a high quantum efficiency (typically 20-30%) over the wavelength range of the scintillator. Typical values of the emission wavelength of various organic scintillators are given in Table 2-5. A 10-stage dynode photomultiplier tube type 9266B (Electron Tubes) of 52 mm diameter, was connected to the BC523A cell. It was chosen for its spectral sensitivity that covers a range of 310-650 nm, with quantum efficiency (QE) of 28% as shown in Figure 3-3.

The 9266B tube is valued for its excellent timing performance (rise time of 4 ns, pulse width of 5.5 ns, and a transit time of 37 ns). Another photomultiplier tube type 9125B (30mm diameter) was connected to the BGO, which has a similar spectral range to the one described above. The bias voltage was set at +900V for the two photomultiplier tubes. This value was determined by irradiating the detector in each case with $^{137}$Cs source and increasing the bias voltage in equal steps of 20 V while the other parameters of the system such as the amplifier gain (9x) and shaping time (0.5 µs) are kept constant. The change in the centroid channel number of the 662 keV γ-ray photopeak was recorded on the MCA and plotted versus the bias voltage. For example in the case of the photomultiplier connected to the BGO, the plot is shown in Figure 3-4.

![Figure 3-3](image)

**Figure 3-3** The spectral sensitivity (QE ~ 28%) of a photocathode used with the 52mm-photomultiplier tube type 9266B. Data in the plot was taken from the supplier specification sheet (Electron Tubes).
Figure 3-4  The optimum bias voltage (+900 V) for the photomultiplier connected to the BGO.

The liquid scintillator cell has a glass window at the end coupled to the photomultiplier tube. This window is made up of a 3 mm standard window glass, and was tested using an UV-visible spectrophotometer. The result of the test is shown in Figure 3-5, where transmission of visible light is flat and reaches up to 80% at BC523A detector typical emission wavelength values (425 nm). Optical coupling between the liquid scintillator glass window (refractive index 1.415) and the photomultiplier glass (refractive index 1.480) was done carefully by joining the two windows using high viscosity silicon oil to facilitate the transmission of optical photons through the interface.

Figure 3-5  The transmission curve of the 3mm thick window glass, indicating that the visible light is flat and reaches up to 80% at BC523A detector typical emission wavelength values (~ 425 nm).
For pulse counting purposes, a special integrated circuit was fitted (voltage divider type Electron tube C647), which was connected to the pins of the photomultiplier tube base (socket type B14A). The voltage divider is applied to the photomultiplier to accelerate photoelectrons on to the first dynode, to accelerate the secondary electrons between successive dynodes and to collect the electrons from the last dynode at the anode. This is achieved by a resistance distribution as shown in Figure 3-6. The value of each resistor is \( R = 330 \, \text{K\Omega} \), and \( R(\text{total}) = 6.6 \, \text{M\Omega} \). The increasing potential difference causes the electrons to further accelerate when passing through each successive dynode (especially at the last few stages where it must be increased to overcome space charge effects). The resistor (\( R_i \)) shown in Figure 3-6 is the load resistor (typically 10k\Omega to 1M\Omega) to enable the anode signal to pass through the capacitor (C) that is connected to the circuit to collect the charge. This capacitor also isolates the DC potential at the anode from the measuring electronics. A safety resistor (\( R_S = 10 \, \text{M\Omega} \)) is added to prevent the anode floating back to the dynode potential when the external load is removed.

![Figure 3-6](image)

Figure 3-6  A schematic diagram of the tapered voltage divider type C647.

### 3.4 The neutron source and apparatus

The assembled liquid scintillator detector was irradiated with fast neutrons and gamma radiation produced from an Am-Be neutron source of 18.02 GBq (0.487 Ci). The fast neutron spectrum produced from this source is shown in Figure 3-7, taken from (Geiger and Van Der Zwan 1975). The source also emits a significant number of \( \gamma \)-rays as a consequence of the reaction shown in Figure 3-7. The neutron emission rate \( N \) for 1 Ci of this source is 2.2x10^6 neutrons/sec, so using Equation 2-55, the fluence \( \phi \) at a distance \( d = 57 \, \text{cm} \) (source-detector distance) is \( \sim 26.2 \, \text{neutrons/cm}^2\text{sec} \).
$^{241}$Am decays to $^{237}$Np emitting $\alpha$ (5.5 MeV), and the neutron is produced via the reactions:

$^9$Be($\alpha$, n)$^{12}$C + 5.7 MeV, or

$^9$Be($\alpha$, n)$^{12}$C$^*$ (Ex=4.43 MeV) + 1.3 MeV followed by $\gamma$-decay of the $^{12}$C$^*$ emitting a 4.43 $\gamma$-ray.

**Figure 3-7** The energy distribution of Am-Be source showing the nuclear reactions that produce the neutron in the source, data in plot were previously reported (Geiger and Van Der Zwan 1975).

The neutron source was attached to the top of a support beam contained in a water tank as shown in Figure 3-8. The active part (the cell) of the cylindrical BC523A liquid scintillator detector was positioned on the same vertical plane above the source. To produce fast neutrons a sealed air-filled plastic tube was placed into the water tank and positioned above the source using steel rods and clamps.

Using Equation 2-56, the effective dose equivalent $H_e$ absorbed by a human body exposed to radiation from the tank, with no air tube, at 2 m from the source was estimated to be 0.06 µSv/hr.

**Figure 3-8** A schematic of the neutron source contained within a water tank. An air filled adjustable tube is used to vary the proportion of fast neutrons incident on the detector.
3.5 Circuit description

Initial measurements of PSD and energy resolution in BC523A used a relatively simple circuit shown in Figure 3-9. Pulses from the BC523A detector were passed through the charge integrating preamplifier type 113 (Ortec). The preamplifier was connected to a waveform digitiser (WFD) type Cougar (Acqiris), described in more detail in the following section.

Figure 3-9 A block diagram of the digital system used to test the PSD properties of BC523A.

The preamplifier integrated the current pulses from the photomultiplier tube. Thus, a simple 10-90% rise time PSD algorithm was applied to the pulse leading edge. Initial tests with the simple 10-90% rise time algorithm described in Equation 2-60 were performed on the leading edge of integrated pulses from BC523A liquid scintillator using a digital oscilloscope. The detector was irradiated with $^{22}\text{Na}$ gamma ray source. A typical preamplifier pulse (complete waveform) captured by the digital oscilloscope is shown in Figure 3-10. The measured rise times were fast and ranged from 10-30 ns.

Figure 3-10 Typical rise time of an integrated pulse from BC523A irradiated by Na-22 gamma ray source. The measured 10-90% rise time of this pulse is 28.5 ns.
3.6 Acqiris waveform digitiser

Because pulse shapes from liquid scintillators (e.g. BC523A) have extremely fast decay times (Figure 3-10), consequently the use of digital PSD relies on fast waveform digitisers with few ns timing resolution. The WFD type Cougar is a compact PCI crate-based system that includes a high speed flash analogue-to-digital (ADC) converter, which samples waveforms in real time mode at rates of 1 Gs/s with an 8-bit resolution and 2Mpoints waveform memory. Therefore, the complete shape of the detector pulse was captured with a 1 ns time resolution (intervals). The WFD used in this work has a limited 8-bit amplitude resolution that is a necessary trade-off in order to obtain very fast sampling rates. This compares with commercial digital spectroscopy systems\(^1\) that have 12 or 14-bit energy resolution but only offer a 25 ns sample interval which is insufficient for use with fast organic scintillators.

<table>
<thead>
<tr>
<th>Acqiris setting</th>
<th>High gain</th>
<th>Low gain</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample interval (s)</td>
<td>1x10(^{-9})</td>
<td>1x10(^{-9})</td>
</tr>
<tr>
<td>Number of samples</td>
<td>200</td>
<td></td>
</tr>
<tr>
<td>Full scale (V)</td>
<td>500x10(^3)</td>
<td>5</td>
</tr>
<tr>
<td>Trigger level (V)</td>
<td>-0.02</td>
<td>-0.2</td>
</tr>
</tbody>
</table>

Histogram setting (Labview)

1- Energy (pulse height)

<table>
<thead>
<tr>
<th>Full scale (V)</th>
<th>High gain</th>
<th>Low gain</th>
</tr>
</thead>
<tbody>
<tr>
<td>500x10(^3)</td>
<td></td>
<td>5</td>
</tr>
</tbody>
</table>

| Channels | 256 |

2- Rise time (ns)

<table>
<thead>
<tr>
<th>Full scale (V)</th>
<th>High gain</th>
</tr>
</thead>
<tbody>
<tr>
<td>130x10(^3)</td>
<td></td>
</tr>
</tbody>
</table>

| Channels | 130 |

\(^1\) For example XIA (http://www.xia.com).
An 800 MHz Pentium III PC computer running dedicated LabView data acquisition software for real-time pulse analysis and histogramming was used to capture the digitised waveforms on an event-by-event basis (Sellin 2000). The LabView software extracted the energy and rise time from each pulse and performed histogramming of the data. The Labview software also controls the WFD setting. Two sets of WFD parameters were used (Table 3-1), which provided high and low gain settings; a high gain setting to investigate the charged particle events due to thermal neutron capture, and a low gain setting to measure higher energy neutron and gamma ray events are shown.

The WFD was checked with a square pulse from a fast generator connected to the test input of the preamplifier. Typical rise times values measured from integrated pulses showed a symmetric Gaussian response function with a peak centroid of 31.7 ns, FWHM = 1.7 ns and resolution of 5.5 %. Pulses were reproduced using a digital oscilloscope that measured rise times consistent with the WFD measurements within few percent of error.

The WFD was used to digitise pulses produced in both the current and integrated modes. The preferred mode was the integrated mode (preamplifier pulse) due to its higher signal-to-noise ratio. The electronic noise (random fluctuation voltage level) persists even if the signal is removed. In an electronic circuit, this noise would not alter the size of the pulse, but only the precision with which it is measured (there is a basic limit below which signals becomes masked by noise and can no longer be detected among it). Any true signal from the detector measured as a voltage is done in the presence of this underlying uncertain noise level. The smaller the true signal is, relative to the noise level, the greater the effect of the noise on the final measurement. It is thus very important to maintain a good signal-to-noise ratio throughout the entire signal chain, so that the minimum digital threshold can be set without significant contribution from the noise to the real captured pulses.

To explore the effect of the preamplifier in enhancing the signal-to-noise ratio Figure 3-11 shows typical low amplitude pulses acquired on the WFD with and without the preamplifier. The pulses are produced by 59.5 keV gamma rays from $^{241}$Am, and are acquired with different relative electronics gain in each case. With a pulse amplitude that is only approximately 10% of the full dynamic range of the digitiser, the effect of the 8-bit resolution can be clearly seen. The upper figure shows the 10-90% rise time algorithm that is applied to the integrated pulse. The equivalent PSD algorithm is to be applied to the non-integrated current pulse is a 'time over threshold' measurement of the pulse width. This requires setting a software threshold as low as possible without causing false triggers due to signal noise. In Figure 3-11 the non-integrated pulse is shown with a software threshold indicated at −1 mV.
which is the minimum level possible. At this level, some signal noise can be seen to exceed the threshold level. The algorithm also allowed automatic thresholding - by setting a level 5\(\sigma\) the 1\(\sigma\) noise on the baseline signal. Consequently in this work, a 10-90\% rise time algorithm was applied to the integrated pulse due to the noise affecting the time over threshold measurement. Typical high amplitude integrated and current pulses acquired using the digital system were recently demonstrated (Jastaniah and Sellin 2003).

![Figure 3-11](image)

**Figure 3-11** Typical integrated pulse from the preamplifier (upper) and a current pulse from the photomultiplier tube anode (lower) produced from 59 keV gamma rays from \(^{241}\)Am. The system gain is different in each case.

It was of interest to compare the pulse height spectra that were produced from the WFD with those obtained using a conventional 12-bit analogue spectroscopy ADC, and to compare the energy resolution of both systems. A \(^{60}\)Co spectrum was acquired using a high purity germanium (HPGe) detector, using both a conventional 12-bit analogue MCA system, and
our 8-bit digital system. The pulse height spectra of both systems are shown in Figure 3-12 and Figure 3-13 respectively. Because of the difference in the ADC resolution for both systems, the digital system was of the order of three times worse (R=1.2%), than the analogue system (R=0.4%)

![Digital spectrum R = 1.2%](image1.png) ![Analogue spectrum R = 0.4%](image2.png)

**Figure 3-12** Co-60 energy spectrum using the digital pulse processing system connected to an HPGe detector.  
**Figure 3-13** Co-60 energy spectrum using the analogue pulse processing system connected to an HPGe detector.

### 3.7 Energy calibration

#### 3.7.1 Description of the calibration technique

Analogue and digital pulse processing systems were connected simultaneously to the BC523A liquid scintillator, and were calibrated using various γ-ray sources. With the systems calibrated, they were used to identify the boron capture peak and other higher energy events observed on the energy spectrum obtained from BC523A irradiated by Am-Be source. Because organic scintillators are relatively low Z-materials, the Compton scattering is dominant and Compton edges of the only distinguishable feature in the pulse height spectrum. Therefore, the energy calibration using gamma ray sources was based on the Compton edge channel number values that were calculated using Equation 2-16 and listed in Table 3-2 (the maximum energy of a Compton recoil electron). However, it was possible to obtain X-ray photopeaks from Tb (47.5 keV) and low energy gamma ray sources such as $^{241}$Am, which were used to calibrate the detector at high gain.
### Table 3-2 Calculated Compton edges energy for $\gamma$-ray sources.

<table>
<thead>
<tr>
<th>Source</th>
<th>Compton Edge Energy (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{133}\text{Ba}$</td>
<td>0.197</td>
</tr>
<tr>
<td>$^{22}\text{Na}$</td>
<td>0.341</td>
</tr>
<tr>
<td>$^{137}\text{Cs}$</td>
<td>0.477</td>
</tr>
<tr>
<td>$^{60}\text{Co}$</td>
<td>1.041</td>
</tr>
<tr>
<td>$^{24}\text{Na}$</td>
<td>1.062</td>
</tr>
</tbody>
</table>

In order to precisely locate the Compton edge on the spectrum for the calibration process, the calibration procedure used the channel number 75% up the Compton edge (Cherubini, Moschini et al. 1989). The Compton edge point $X_c$ that corresponds to the channel number of 75% up the Compton edge continuum in each case was estimated as follows:

$$X_c = \left( \frac{X_H - X_L}{2} \right) + X_H$$

Equation 3-1

were, $X_H$ is the highest count point up the Compton edge continuum and $X_L$ is the point with half the maximum counts, so $X_c$ should lie in the middle point between both ends.

### 3.7.2 Calibration data

Calibration was initially carried out using the analogue MCA. A single gain was used to cover photon energies from 0-350 keV. Separate calibrations (Table 3-3) were carried out for the small and large BC523A cells, which showed different light output (amplifier gain of 9x and 500x respectively). The shaping time was set at 0.5$\mu$s in both cases. An example of the plotted calibration data is shown in Figure 3-14 for the small BC523A.
Table 3-3  Energy calibration sources for analogue detection system using BC523A detector.

<table>
<thead>
<tr>
<th>Detector</th>
<th>Source</th>
<th>E&lt;sub&gt;c&lt;/sub&gt;, E&lt;sub&gt;c&lt;/sub&gt;', (keV)</th>
<th>Channel number</th>
<th>Error (±) channels</th>
</tr>
</thead>
<tbody>
<tr>
<td>BC523A (small)</td>
<td>Tb(Kα,Kβ)</td>
<td>47.5</td>
<td>28</td>
<td>8.5</td>
</tr>
<tr>
<td></td>
<td>241 Am</td>
<td>59.5</td>
<td>37</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>133 Ba</td>
<td>E&lt;sub&gt;c&lt;/sub&gt; = 197</td>
<td>100</td>
<td>19</td>
</tr>
<tr>
<td></td>
<td>22 Na</td>
<td>E&lt;sub&gt;c&lt;/sub&gt; = 341</td>
<td>200</td>
<td>32</td>
</tr>
<tr>
<td>BC523A (large)</td>
<td>Tb(Kα,Kβ)</td>
<td>47.5</td>
<td>83</td>
<td>14</td>
</tr>
<tr>
<td></td>
<td>241 Am</td>
<td>59.5</td>
<td>110</td>
<td>18</td>
</tr>
<tr>
<td></td>
<td>133 Ba</td>
<td>E&lt;sub&gt;c&lt;/sub&gt; = 197</td>
<td>933</td>
<td>92</td>
</tr>
</tbody>
</table>

Figure 3-14  The calibration data for analogue detection system connected to the small BC523A, using compton edges of the Na-22 and the Ba-133 sources. For Am-241 and Tb, the photopeak energy was taken.

Using the digital pulse processing system, the energy calibration curve for BC501A using the high gain setting is shown in Figure 3-15. The data in the curve was determined using a variable target 241 Am X-ray source, with weighted mean energies taken for Ba, Tb targets, and a 59.5 keV 241 Am gamma ray source as shown in Table 3-4. The table also lists calibration data for other scintillators at high gain setting. In the case of the large BC523A

\[ E_c \] is the Compton edge energy given in Table 3-2
detector, the high gain on the digitiser was set to 200mV instead of 500mV, and an additional 1GHz current preamplifier was used, which has a gain of 100.

![Graph with fit equation: \( Y = 585X - 4 \)]

**Figure 3-15** The calibration data for BC501A at high gain setting, using photopeaks from two X-ray sources and one gamma ray source. The shown line is the best fit to the data.

<table>
<thead>
<tr>
<th>Detector</th>
<th>Source</th>
<th>( E, E_c ) (keV)</th>
<th>Channel number</th>
<th>Error (±) channels</th>
</tr>
</thead>
<tbody>
<tr>
<td>BC501A</td>
<td>Am-241</td>
<td>59.5</td>
<td>31.1</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>Tb(Kα,Kβ)</td>
<td>47.5</td>
<td>24.3</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>Ba(Kα,Kβ)</td>
<td>34</td>
<td>16.2</td>
<td>3</td>
</tr>
<tr>
<td>BC523A (small)</td>
<td>Am-241</td>
<td>59.5</td>
<td>19.1</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>Tb(Kα,Kβ)</td>
<td>47.5</td>
<td>15.1</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Ba(Kα,Kβ)</td>
<td>34</td>
<td>10.6</td>
<td>3</td>
</tr>
<tr>
<td>BC408</td>
<td>Am-241</td>
<td>59.5</td>
<td>31.2</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Tb(Kα,Kβ)</td>
<td>47.5</td>
<td>26.5</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>Ba(Kα,Kβ)</td>
<td>34</td>
<td>18.0</td>
<td>3</td>
</tr>
<tr>
<td>BC523A (large)</td>
<td>(^{241})Am</td>
<td>59.5</td>
<td>16</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>(^{133})Ba</td>
<td>Ec = 197</td>
<td>50</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td>(^{137})Cs</td>
<td>Ec = 477</td>
<td>120</td>
<td>18</td>
</tr>
</tbody>
</table>

**Table 3-4** Data for high gain calibration using X-rays and gamma rays sources.
For the low gain setting, higher energy gamma ray sources were used to calibrate the detector. A calibration curve for BC501A is shown in Figure 3-16. The data in the curve were determined using the gamma ray sources listed in Table 3-5. The table also shows data for BC408 and the small BC523A (Jastaniah and Sellin 2002).

Figure 3-16  The calibration data of BC501A at low gain setting, using Compton edges from three gamma ray sources. The shown line is the best fit to the data.

Table 3-5  Data for low gain calibration using gamma rays sources at Compton edge energy.

<table>
<thead>
<tr>
<th>Detector</th>
<th>Source</th>
<th>E_C (keV)</th>
<th>Channel number</th>
<th>Error (+/-) Channels</th>
</tr>
</thead>
<tbody>
<tr>
<td>BC501A</td>
<td>^{133}Ba</td>
<td>197</td>
<td>12</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>^{137}Cs</td>
<td>477</td>
<td>31</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>^{60}Co</td>
<td>1041</td>
<td>67</td>
<td>2</td>
</tr>
<tr>
<td>BC523A (small)</td>
<td>^{133}Ba</td>
<td>197</td>
<td>7</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>^{25}Na</td>
<td>341</td>
<td>13</td>
<td>1</td>
</tr>
<tr>
<td></td>
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<td>2</td>
</tr>
<tr>
<td></td>
<td>^{60}Co</td>
<td>1041</td>
<td>43</td>
<td>2</td>
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<td></td>
<td>^{25}Na</td>
<td>1062</td>
<td>44</td>
<td>2</td>
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<tr>
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<td>^{137}Ba</td>
<td>197</td>
<td>12</td>
<td>1</td>
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<tr>
<td></td>
<td>^{133}Cs</td>
<td>477</td>
<td>31</td>
<td>1</td>
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<tr>
<td></td>
<td>^{60}Co</td>
<td>1041</td>
<td>70</td>
<td>2</td>
</tr>
</tbody>
</table>
3.8 Spectral performance

3.8.1 Analogue versus digital spectra

It is of interest to compare the spectra from the BC523A connected to the analogue and the digital systems. X-ray photopeak spectra from Tb (47.5 keV) using both the 8-bit digital system and a 12-bit analogue MCA were obtained. These spectra are shown in Figure 3-17 and Figure 3-18 respectively. Both show a broad photopeak from a mixture of $K_\alpha$ and $K_\beta$ lines in Tb. The measured FWHM energy resolution of both spectra obtained by the digital and analogue systems are $R=55\%$ and $R=67\%$ respectively, which is dominated by the response of the liquid scintillator. The low energy threshold of the digital spectrum is slightly higher than for the MCA, with pileup events appearing as a 'fake' peak at zero channel number in Figure 3-17. The arbitrary horizontal gain of the two spectra is not equal.

![Figure 3-17](image1)

Figure 3-17 Energy spectrum of Tb source using an 8-bit digital pulse processing system connected to BC523A detector.

![Figure 3-18](image2)

Figure 3-18 Energy spectrum of Tb source using a 12-bit analogue MCA connected to BC523A detector.
Digital spectra from different gamma ray energies were also obtained. Typical gamma ray energy spectra using BC501A connected to the digital pulse processing system set at high gain are shown in Figure 3-19. Broad photopeaks from (a) a mixture of Kα and Kβ lines in Ba, (b) a mixture of Kα and Kβ lines in Tb, and (c) 241Am gamma rays are observed. The measured FWHM energy resolutions of spectra are 37%, 41%, and 55% respectively and are dominated by the response of the liquid scintillator.

**Figure 3-19**  X-ray and gamma ray spectra detected by BC501A detector, showing broad photopeaks obtained with three sources from (a) a mixture of Kα and Kβ lines in Ba, (b) a mixture of Kα and Kβ lines in Tb, and (c) 241Am gamma ray.

Using the same detector at low gain setting, gamma ray Compton edge spectra from three known gamma ray energies sources (a) 133Ba (0.197 MeV), (b) 137Cs (0.477 MeV), and (c) 60Co (1.041 MeV) were obtained as shown in Figure 3-20. The observed Compton edges are indicated by energies in MeV and corresponding channel numbers.
Figure 3-20 Gamma ray spectra showing Compton edges that are indicated by energies in KeV and corresponding channel number from three sources (a) $^{133}\text{Ba}$, (b) $^{137}\text{Cs}$, and (c) $^{60}\text{Co}$.

3.8.2 Mixed radiation field

The response function of the BC523A detector due to neutrons and gamma rays from the neutron tank was explored using both analogue and digital pulse processing systems. Using the digital pulse processing system connected to the small BC523A, the high gain setting was used to acquire a pulse height spectrum from the Am-Be source. A simple maximum height algorithm was used to extract the amplitude of each pulse and no PSD was applied to the data at this stage. Figure 3-21 shows the resulting energy spectrum that contains the broad neutron capture peak on top of a continuum of events. Based on the digital system calibration, the $^{10}\text{B}$ neutron capture peak was observed at channel number 20 ± 5 that correspond to an electron-equivalent energy of 60 ± 15 keV. This low energy value observed from the energetic
charged particles is due to the low light response of the liquid scintillator to heavy charged particles, as previously reported (Aoyama, Honda et al. 1993). The continuum in the higher energy region is due to the combination of Compton scatter events from gamma rays produced from the source, and proton recoil events from fast neutrons.

Figure 3-21 Energy spectrum obtained from BC523A detector irradiated with Am-Be source using the digital pulse processing system.

Figure 3-22 shows the corresponding spectrum due to fast and slow neutrons and gamma ray events using the analogue pulse processing system. The same spectral features can be observed as in Figure 3-21, with the $^{10}$B capture peak at an energy of $58\pm10$ keV electron equivalent. Similarly the response of the large BC523A to fast and thermal neutrons from Am-Be source using the analogue pulse processing system was determined, where the broad $^{10}$B neutron capture peak appeared at an energy of $58\pm23$ keV.
3.9 Pulse shape discrimination data

3.9.1 Digital Algorithm

Two typical waveforms observed from the output of the charge integrating preamplifier connected to BC523A detector, produced by γ-ray and fast neutron interactions are shown in Figure 3-23. The slower tail of the neutron pulse in the figure is clearly shown, and can be detected by the 10-90% rise-time algorithm. In these typical waveforms the measured risetimes are 10-20 ns for electrons (γ-ray interactions) and 40-100 ns for protons (fast neutron scatter interactions). The digital pulses in Figure 3-23 show amplitudes of ~ 560 mV for the γ-ray pulse and ~ 2.1 V for the neutron pulse. The number of samples in each waveform capture was 200, covering the time range of 0-400 ns.

Digital filtering was used to remove the high frequency random noise components from the signal, using a five-point binomial-smoothing filter (Marchand and Marmet 1983).
Figure 3-23  Digitised pulses from BC523A due to (upper) a gamma ray source, and (lower) a fast neutron. The marker lines indicate the 10-90% rise time interval.

3.9.2  The two-dimensional plot of rise time versus energy

The labview software was used to acquire pulse height and rise time histograms from the captured waveforms in real time. The software also plotted the data in the form of a two-dimensional (2D) histogram of pulse rise time versus energy in order to show n/γ discrimination. Using the small BC523A at low gain (Figure 3-24), the algorithm provides n/γ discrimination between fast neutrons scatter and γ-ray events (dominated by Compton scatter). The 2D plots have notable features in terms of the shape of each class of events. γ-ray events lie on a well-resolved horizontal 'line' with rise time of 15-20 ns, which is probably limited by the preamplifier rise time. The neutron scattering events lie on a well-separated locus, varying from ~ 30 ns rise time at high energy to ~ 60 ns rise time at low energy. When BC501A is used at low gain (Figure 3-25), the algorithm also provides n/γ discrimination between fast neutron scatter in the scintillator, and γ-ray events. Although there is clear n/γ discrimination between the two classes of events in both materials, with some evidence of slightly better PSD capability in BC501A than BC523A.
Figure 3-24  Rise time versus pulse height plot at low gain setting showing fast n/γ PSD from BC523A detector.

Figure 3-25  Rise time versus pulse height plot at low gain setting showing fast n/γ-rays PSD from BC501A detector.
As a comparison to the liquid scintillators, a similar 2D plot of rise time versus pulse height was also obtained using a standard plastic scintillator (BC408) at low gain setting, there was no PSD observed (Figure 3-26). This data confirms the lack of PSD in this material (Birks 1964).

![Figure 3-26 Rise time versus pulse height plot at low gain setting from BC408 detector, demonstrating the lack of PSD from this material.](image)

At the high gain setting, the 2D plots showed different features in each case when a different detector is used. Using the small BC523A (Figure 3-27), the events due to the boron capture peak are clearly visible, but is not separated from the gamma ray events by PSD as has been reported previously (Chou and Horng 1993). This class of events is not present in the 2D plot obtained using the BC501A (Figure 3-28), obviously due to the absence of the boron in this scintillator material. However, the 2D plots at high gain setting using both BC523A and BC501A show good n/γ discrimination, but due to the high gain, the proportion of neutron events present in each spectrum is small because the spectrum is dead-time limited by the more intense low energy γ-ray events, so fast neutrons are only weakly visible.

For these detectors, in both high and low gain setting, the gamma ray events show blurring at the low pulse height region that is due to electronic noise affecting the amplitude algorithm for small pulses.
Figure 3-27  Rise time versus pulse height plot at high gain setting showing n/γ PSD from BC523A, but with poor capture n/γ PSD, where the $^7$B thermal neutron capture events is clearly visible, smeared towards longer rise times.

Figure 3-28  Rise time versus pulse height plot at high gain setting showing n/γ PSD from BC501A detector.
Similar two dimensional plots of rise-time versus pulse height were also obtained for the standard plastic scintillator (BC408) at high gain setting, where there was no PSD observed (Figure 3-29).

![Figure 3-29 Rise time versus pulse height plot at high gain setting from BC408 detector.](image)

Similar PSD tests at high and low gain settings were performed using the large BC523A detector that was locally prepared. At low gain, no PSD between neutrons and gamma rays was observed (Figure 3-30) due to Oxygen-induced quenching that dramatically affected the PSD properties. This was probably caused by the long storage time of the liquid scintillator before use.
3.9.3 Performance of the digital PSD algorithm

The question that arises when looking at those two-dimensional plots of rise time versus energy performed using the digital algorithm is how to evaluate the degree of separation between the neutrons and gamma ray peaks? This was evaluated by applying energy gates to the two-dimensional data of the 10-90% rise time in which a FOM value may be obtained as described by Equation 2-61. Two energy (pulse height) gates were applied at low (channels 10-49) and high (channels 165-240) to the scintillators that show PSD capabilities.

Using the small BC523A at low gain (Figure 3-24), a corresponding rise time distributions at low and high energy gates are obtained as shown in Figure 3-31.

Figure 3-30 Rise time versus pulse height plot at low gain setting from large volume BC523A detector, demonstrating the poor n/γ discrimination due to oxygen-induced quenching.
In Figure 3-31, The FOM values deduced from these data are (a) 1.0 and (b) 1.2. The FOM for the low energy events (a) is reduced due to the effect of noise on the low amplitude pulses, which tends to broaden the peaks. The FOM values show a similar trend to conventional analogue PSD data (Wang, Hsu et al. 1999), which typically shows a convergence of neutron and gamma events in two-dimensional space at low energy. In this digital 10-90% rise time algorithm, the distribution of events in two dimensional rise time-energy space is different to analogue systems, but the under-lying degradation of FOM at low energy is similar.

When applying the energy gates to the two-dimensional data of BC501A at low and high gains (Figure 3-25 and Figure 3-28) the corresponding rise time distributions at low and high energy gates are obtained. The resulting rise time spectra are shown in Figure 3-32 and Figure 3-33 respectively, where the FOM values deduced from the low gain data are (a) 1.4 and (b) 1.5 and FOM values deduced from the high gain data are (a) 1.4 and (b) 1.4.
Figure 3-32  Rise-time spectra projected from the data in Figure 3-25. The PSD FOM in each case is (a) 1.4 at low energy and (b) 1.5 at high energy.

Figure 3-33  Rise-time spectra projected from the data in Figure 3-28. The PSD FOM in each case is (a) 1.4 at low energy and (b) 1.4 at high energy.
3.9.4 Tests with no preamplifier

The digital PSD performance of current pulses (no preamplifier connected) acquired from BC501A were also investigated to make a direct comparison against integrated pulses. The data acquisition was performed at a low gain setting (2V full scale). A 2D plot of pulse rise time, derived from the time over threshold algorithm, versus pulse energy of different events at low gain setting shows the resulting n/γ discrimination (Figure 3-34). The measured n/γ PSD was less than the one achieved with the use of a preamplifier because the FOM approach is less well defined in terms of projection of this data for low pulse amplitudes due to overlap between the neutron and γ-ray events. The FOM values obtained from Figure 3-34 range from 0.8 at low energy to 1.4 at high energy. In addition to that, the rise time was not short as expected from a liquid scintillator (typically few ns). The effect is therefore probably related to the photomultiplier tube timing characteristic. In Figure 3-34, the gamma ray events that appear to be curved in its shape is not a physical quantity, but it is due to the noise affecting the algorithm (time over threshold) and so it get worse at lower pulse heights where it becomes more blurred.

**Figure 3-34** Rise time (derived from time-over-threshold described in Table 2-7) versus pulse height plot at low gain setting from BC501A with no preamplifier connected (current pulses).
3.10 Discussion

In this chapter, an important question was answered: Knowing that PSD has potential applications for neutron monitors, are digital PSD algorithms feasible? The application of digital pulse shape algorithms to n/γ PSD in BC523A is discussed and its PSD performance is compared with some other organic scintillators. Using an 8-bit 1GS/s waveform digitiser, the scintillation detector signals were sampled with nanosecond time resolution to extract event parameters such as pulse height and rise time. Hence the variations in pulse shape and rise time for gamma rays and neutrons has been studied and the quality of separation of these events was estimated. Even using a simple 10-90% rise time algorithm, it was possible to observe good gamma/neutron separation, and FOM obtained using this digital technique was presented. Thus digital PSD algorithms can be employed to reduce the unwanted signals from gamma ray induced events in the scintillator.

The digital PSD performance in terms of the measured FOM using BC523A at low gain setting (FOM = 1.2 for a high energy gate) was consistent with that obtained (FOM = 1.2) using a conventional analogue method (Chou and Horng 1993), where the radiation source used in both cases was Am-Be. Similarly, the digital PSD performance using the unloaded scintillator (BC501A) at low gain setting (FOM = 1.5 for a high energy gate) was close to the obtained value (FOM = 1.7) using the analogue method by Chou. The quality of separation in the 2D plots obtained using BC523A and BC501A are comparable to the most recently reported studies, which uses direct waveform digitisation of PMT pulses to investigate digital PSD performance both in stilbene (Kornilov, Khriatchkov et al. 2003) and in liquid scintillators (Marrone, Cano-Ott et al. 2002). However, one important advantage of this work over such studies is that it uses a simple PSD algorithm, which has minimal computational overhead, consequently are most suitable for the implementation of fast real-time pulse processing in field instruments. While the two studies by Kornilov and Marrone, have concentrated on more complex pulse shape analysis, typically using linear regression techniques to fit a calculated response function to each pulse. Such techniques are highly computationally intensive and poorly suited for real-time processing in potential field instruments.
Chapter 4  Capture-gated neutron detection

4.1 Introduction

The aim of the experiment presented in this chapter was to develop a portable neutron monitor that is capable of fast neutron detection and spectroscopy in the presence of strong mixed n/γ radiation fields. In particular, the suitability of BC523A for capture-gated neutron detection using digital data acquisition techniques is presented. The energy of the incident fast neutron can be directly measured from the amplitude of the neutron moderation pulse using a simple digital pulse height algorithm. Additionally, digital capture of the full pulse shapes allows the use of software-based PSD algorithms to further eliminate gamma events that have produced a false capture-gated signal.

Because BC523A has a significantly higher 10B concentration (5% by weight) than BC523 and BC454 plastic scintillator, it has a correspondingly shorter neutron capture lifetime leading to some advantages in terms of lower chance coincidence rates and shorter detector dead-times. Due to the limited capture-gated neutron detection efficiency expected from the small BC523A cell (~105 cm³), a larger cell was designed (Figure 3-1) with a volume of ~685 cm³. This large BC523A detector was also tested for capture-gated neutron spectroscopy, and the fast neutron detection efficiency for both spectrometers is compared.

4.2 Circuits description

To investigate the capture-gated neutron detection mode and to achieve rejection of both unwanted events i.e. gamma ray events and neutron-induced proton recoils events that escape from the detector, an analogue trigger circuit was used to gate the waveform digitiser...
(Figure 4-1). The trigger circuit used a time-to-amplitude converter (TAC) type Ortec 567 to identify capture-gated events with the characteristic ‘moderation–capture’ double pulse sequence. The TAC converts the time interval between the two pulses (recoil-capture) into a pulse that is recorded by the MCA, with an amplitude proportional to the neutron capture lifetime, i.e. the time interval between start and stop input pulses. In timing measurements involving very short time separated events, shaping the pulse using a standard shaping amplifier with a shaping time of the order of a few microseconds will contribute to a significant timing error. Instead a time filter amplifier (TFA) type Ortec 474 was used to amplify the pulse with a shaping time of only a few nanoseconds. The TFA provides a continuously adjustable gain (2x to 250x) and a separately selectable RC time constant i.e. integrate and differentiate ranging from as low as 4 ns up to 0.5 µs. Two TFA modules were used to buffer the output pulses from the small BC523A and provide impedance matching of fast signals into the waveform digitiser. TFA1 was set at low gain (16x) suitable for detection of the high-energy scatter event (proton recoil pulse), whereas TFA2 was set at a high gain (250x) suitable for the low energy boron capture event (charged particle pulse). TFA1 also provided the amplified pulse signal to the digitiser. In Figure 4-1, the first signal (upper) is processed though a single channel analyser (SCA1) with a wide window, corresponding to neutron scatter pulses, and forming the TAC start pulse. The second signal (lower) is processed though another single channel analyser (SCA2) with a tight widow around the boron capture peak forming the TAC stop pulse.

![Figure 4-1](image-url) The block diagram of capture-gated neutron detection circuit using the small BC523A cell.
In the second part of the experiment when the large BC523A was used for capture-gated neutron detection, the trigger circuit was modified as shown in Figure 4-2. A linear high bandwidth (1 GHz) preamplifier with an amplification of 100x was used to amplify the current signal from the PMT. Two pulse processing chains are shown in Figure 4-2, the first pulse processing chain (upper) is connected to the BC523A liquid scintillation detector providing the linear signal to the digitiser and the TAC output used to trigger the digitiser whenever the coincidence requirement (1) is fulfilled. Optionally, the second pulse processing chain (lower) is connected to the BGO detector and is used as an additional trigger to the digitiser to form a further coincidence requirement (1)+(2) to be fulfilled before the digitiser can be triggered. These two requirements are controlled by a master coincidence unit. The trigger circuit is designed to operate with requirement (1) or (1) + (2) i.e. the BC523A signals (start then stop) in coincidence or the two BC523A signals plus the BGO signal all together in coincidence.

**Figure 4-2** The block diagram of the modified Capture-gated neutron spectrometer, using the large volume BC523A cell and coincident BGO detector.

### 4.3 Capture-gated double pulse sequence data

The time between the first and second interactions in each double-interaction event is governed by Equation 2-51. Two examples of typical short and long time differences demonstrates the capture-gated event with the characteristic 'moderation–capture' double pulse sequence identified by the TAC module as shown in Figure 4-3, where the signal was
derived from the low gain TFA and captured on a digital oscilloscope. In each TFA signal, the proton recoil pulse (lower left) is a measure of the total KE of the fast neutron. The time between the individual neutron-proton collisions is sufficiently short that the light produced by the resultant multiple recoils is summed into a single-pulse in typically \( \sim 50 \) ns. The capture pulse (lower right) results from detection of the \(^7\)Li + \( \alpha \) reaction products, produced with an energy of \( E_0 = 2.3 \) MeV (94\%) or 2.8 MeV (6\%). Due to the low light response of the liquid scintillator to heavy charged particles, these events produce pulses with an electron-equivalent amplitude of approximately 60 keV.

![Figure 4-3](image-url)

**Figure 4-3** Two typical double-pulse capture-gated neutron sequences (lower traces) from the low gain TFA signal, captured by a digital oscilloscope at long (left) and short (right) time differences, with the TAC trigger pulse also shown (upper trace). The two images show different neutron capture pulse heights due to different scintillation detector used, where the small BC523A cell and large BC523A cell were used to produce the images in the left and right respectively.

### 4.4 Operational characteristics

#### 4.4.1 SCA adjustment

Careful setting of the two SCA windows was required to prevent overlap of the scatter and capture regions and so prevent chance coincidences. To calibrate the SCA for coincidence counting the circuit in Figure 4-4 was used. Only signals that fall within the SCA window were allowed to appear in the MCA spectrum.
A characteristic feature of the capture-gated pulse signature is that the amplitude of the second pulse from the $^{10}$B capture reaction, is monoenergetic allowing the energy window of SCA2 ($E=0.6$ V, $\Delta E=0.8$ V) to be set tightly around 60 keV as shown Figure 4-5, using the high gain TFA2 (250x). In contrast, SCA1 that was used to detect the moderation pulse was set with an energy threshold just above the capture peak and with the energy window widely open ($E=0.1$ V, $\Delta E=6.3$ V) as shown in Figure 4-6. This channel used the low gain TFA1 (16x). This calibration was performed using the small BC523A.

A similar SCA adjustment was carried out using the large volume BC523A cell. The SCA1 that was connected to the TFA1 at low gain (25x) was set at $E=1$ V, $\Delta E = 3$ V and the SCA2 that was connected to the TFA2 at high gain (250x) was set at $E = 0.5$ V, $\Delta E = 1.8$ V.
Figure 4-5  Effect of the SCA in gating the capture peak. The signal was taken from the high gain TFA2, using the small BC523A cell.

Figure 4-6  Setting the scatter SCA1 for the low gain TFA1, using small volume BC523A cell.
4.4.2 TAC Linearity

The TAC spectrum was calibrated over the whole TAC range in order to know the exact time between the 'moderation-capture' double pulse sequences. A timing measurement circuit is shown in the block diagram of Figure 4-7, which tested the linearity of the TAC i.e. the time interval to amplitude conversion. In particular, a pulse from the detector was sent to two timing signal channels. The first signal is processed through an SCA to produce a logic start signal at the input of the TAC, and the second signal with an extra delay generates the stop logic signal required by the TAC. Both TFA1 and TFA2 were kept at a high gain (250x) to create similar signals. These signals are then separated by adding extra time delay (250 ns up to 10 µs) to the TFA2 signal using a delay unit type Ortec 427.

![Figure 4-7](image_url)  
**Figure 4-7** Timing measurement circuit.

The TAC was calibrated over a range of 10 µs when the small BC523A was characterised. However, due to short mean capture time of neutrons in BC523A, it was later found that a range of 2 µs was sufficient, and this was used with the large BC523A. Figure 4-8 shows the linearity curve of the TAC, where the centroid channel number is plotted versus extra time delay. Both SCA1 and SCA2 were set at a tight window around the capture peak (E=0.5 V, ΔE=1.8 V) with the TFA set at a high gain (250x).

Figure 4-8 shows the resulting TAC calibration, which was used in the time difference distribution of Figure 4-16. Similarly, in the case where the small BC523A is used, the fitting equation of \( Y = 812X - 112 \) was used to calibrate the time difference distribution of Figure 4-13 where \( Y \) is in channel number and \( X \) is the extra time delay in nanoseconds.
Figure 4-8  Timing measurements calibration curve (TAC linearity) over 2 µs range using the large volume BC523A cell. Also shown the TAC spectrum using an MCA.

4.4.3 Saturation of TFA signal

The large amplitude proton recoil pulse that corresponds to fast neutron events is most likely to be saturated if measured through the high gain TFA2 channel, leading to undesired signal alteration in the form of undershoot and/or overshoot that could be a source of chance coincidence signals. Therefore, two separate TFA's were used with different gain setting and the signal to the digitiser was only taken from the low gain TFA1 channel. Figure 4-9 shows a typical double pulse taken from the high gain (250x) TFA output signal. The effect of undershoot and overshoot was analysed as shown in Figure 4-10, and the best TFA integrated and differentiated RC time constants setting (that ensure lowest undershoot and overshoot effects) were 50ns and 4ns (minimum setting) respectively as presented in Table 4-1. The time to zero is a measure of how long it takes the signal to go back to the baseline.
Figure 4-9 Typical double pulses with undershoot and overshoot.

Figure 4-10 The effects of undershoot and overshoot on a saturated high gain (250x) TFA signal.
Table 4-1 Optimising TFA setting for high energy pulses from BC523A.

<table>
<thead>
<tr>
<th>Integrated RC time constant (ns)</th>
<th>Differentiated RC time constant (ns)</th>
<th>Undershoot (mV)</th>
<th>Overshoot (mV)</th>
<th>Time-to-zero (ns)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum setting</td>
<td>Minimum setting</td>
<td>-1450</td>
<td>+280</td>
<td>420</td>
</tr>
<tr>
<td>20</td>
<td>Minimum setting</td>
<td>-1350</td>
<td>+120</td>
<td>550</td>
</tr>
<tr>
<td>50</td>
<td>Minimum setting</td>
<td>-1000</td>
<td>Not observed</td>
<td>450</td>
</tr>
<tr>
<td>50</td>
<td>20</td>
<td>-1300</td>
<td>Not observed</td>
<td>420</td>
</tr>
<tr>
<td>50</td>
<td>50</td>
<td>-1350</td>
<td>Not observed</td>
<td>800</td>
</tr>
<tr>
<td>100</td>
<td>100</td>
<td>-1320</td>
<td>Not observed</td>
<td>750</td>
</tr>
</tbody>
</table>

4.5 Small BC523A data

4.5.1 Optimizing the TAC spectra

The TAC spectrum produced using the trigger circuitry is shown schematically in Figure 4-11. After-pulses (source of noise) produced in the photomultiplier tube can create an intense prompt contribution to the TAC spectrum at very short time values. The addition of a small amount of extra delay to the TAC start signal can be used to minimise this effect. Overall the TAC spectrum consists of both true and chance coincidence regions, where the chance coincidences are due to uncorrelated pairs of proton recoil and/or gamma ray events occurring within the TAC range. The use of a narrow SCA window in the capture signal (stop channel) helps to minimise the level of chance coincidences, however the rate of real capture-gated events is much smaller than that of ‘singles’ events due to the small volume of this BC523A cell.

It was necessary to optimise the SCA threshold value in order to reduce the number of chance coincidences to a minimum. By defining a Figure of Merit (FOM) as the ratio of the true coincidence rate \( A/t \) to the chance coincidence rate \( B/t \) (Figure 4-11), optimal setting for the SCA energy windows could be achieved, where \( t \) is the data acquisition time in s. Typical examples demonstrating optimisation of SCA settings for best TAC spectra are presented in Table 4-2. The highest FOM value corresponds to the SCA2 setting of \( E = 0.6 \) V and \( \Delta E = 0.8 \) V, which was used for the capture-gated neutron spectroscopy measurement.
Afterpulses

A (True coincidence)  

B (Chance coincidence)

Time difference

Figure 4-11 The figure of merit (FOM = A/B).

Table 4-2 Optimisation of SCA settings using FOM for best TAC spectra. The data shown is for the small BC523A detector.

<table>
<thead>
<tr>
<th>SCA1</th>
<th>SCA2</th>
<th>A/t (e/s)</th>
<th>B/t (e/s)</th>
<th>FOM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low TFA gain (16x)</td>
<td>High TFA gain (250x)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(scatter pulse)</td>
<td>(capture pulse)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>E = 0.1 V</td>
<td>E = 0.1 V</td>
<td>2.04</td>
<td>3.91</td>
<td>0.52</td>
</tr>
<tr>
<td>ΔE = 6.3 V</td>
<td>ΔE = 1.3 V</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>E = 0.1 V</td>
<td>E = 0.4 V</td>
<td>0.64</td>
<td>0.60</td>
<td>1.07</td>
</tr>
<tr>
<td>ΔE = 6.3 V</td>
<td>ΔE = 1.0 V</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>E = 0.1 V</td>
<td>E = 0.6 V</td>
<td>0.47</td>
<td>0.37</td>
<td>1.27</td>
</tr>
<tr>
<td>ΔE = 6.3 V</td>
<td>ΔE = 0.8 V</td>
<td>(optimum)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The experimentally measured TAC spectrum produced by the trigger circuit and acquired using a conventional multi-channel analyser is shown in Figure 4-12. The true coincidence region (upper plot indicated by the letter A) represents the real capture-gated double peak events. Other regions are also indicated in the plot, such as the chance coincidence (upper plot indicated by the letter B) and the prompt tube after-pulse events (lower plot indicated by the arrow). After logging the spectra in Figure 4-12 (lower plot), the exponential distribution
in the true coincidence region forms a straight line with two exponentials corresponding to early and late time difference true coincidence events. The region above channel number 1000 is due to chance coincidences background.

Figure 4-12  The time difference distribution of the double pulse events.
4.5.2 Mean capture time

Figure 4-13 shows the linear regression applied to the true coincidence portion of the TAC spectrum, with the background chance coincidence subtracted (i.e., a constant value equal to the background counts at channel number 1000). The mean capture lifetime of the thermal neutrons ($\tau = 500 \pm 100 \text{ ns}$) is measured directly from the gradient of this portion of the TAC. The measured value of $\tau$ was consistent with the calculated value of 490 ns (Table 4-3) and also close to the value of 620 ns that was previously predicted using MCNP (Wang, Hsu et al. 1999) as given in Table 2-6. The time constant $\tau$ is sensitive to the time interval (fit interval chosen). Figure 4-13 reveals that the coincidence counting rate decreased exponentially with increasing time after the prompt pulse with a time constant of about 0.5 $\mu$s which reflects the average neutron life-time before capture by $^9\text{B}$.

![Figure 4-13](image)

**Figure 4-13** The distribution of the time differences between the first and the second pulse of the double event after subtraction of chance coincidence background events, showing the mean lifetime of the neutrons in BC523A before capture by $^9\text{B}$. 

<table>
<thead>
<tr>
<th>Time ($\mu$s)</th>
<th>In (counts - BKGD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.52</td>
<td>4.8</td>
</tr>
<tr>
<td>0.54</td>
<td>4.6</td>
</tr>
<tr>
<td>0.56</td>
<td>4.4</td>
</tr>
<tr>
<td>0.58</td>
<td>4.2</td>
</tr>
<tr>
<td>0.60</td>
<td>4.0</td>
</tr>
<tr>
<td>0.62</td>
<td>3.8</td>
</tr>
<tr>
<td>0.64</td>
<td>3.6</td>
</tr>
</tbody>
</table>

*Fit equation:* 

$$Y = -2.15X + 5.7$$

*Mean capture time:* 

$$\tau = 0.5 \pm 0.1 \mu\text{s}$$
The net event rate in the region of true coincidence (0.47 count/s) is a measure of fast neutrons detected using the capture-gated neutron spectrometry method, thus the fast neutron detection efficiency of BC523A can be estimated. Using the air filled tube, the fast neutron flux at 57 cm from the source (source-to-detector) is calculated to be 26.2 neutrons/cm².s, after taking into account the solid angle (Ω=8.32x10³ steradians). The detector side facing the source has a surface area of (5.1 cm x 5.1 cm). Therefore, the rate of neutrons incident on the detector surface area is 680 neutrons/s. Using Equation 2-48, the intrinsic efficiency $\varepsilon_{i}$ of the capture-gated neutron spectrometer exposed to the Am-Be neutron source is ~ 0.1%.

### Table 4-3

The mean capture time of some scintillators calculated at typical thermal neutron energies using Equation 2-52. The optimum value is the lowest in terms of mean capture time that is a function of the $^{10}$B concentration.

<table>
<thead>
<tr>
<th>Scintillator</th>
<th>$N$ (Atoms/cm³)</th>
<th>$^{10}$B %</th>
<th>$\tau$ (µs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BC523A</td>
<td>24.3x10²⁰</td>
<td>~ 5</td>
<td>0.49</td>
</tr>
<tr>
<td>BC523</td>
<td>5.3x10²⁰</td>
<td>~ 1</td>
<td>2.25</td>
</tr>
<tr>
<td>BC454</td>
<td>5.59x10²⁰</td>
<td>~ 1</td>
<td>2.13</td>
</tr>
</tbody>
</table>

### 4.5.3 Comparison with BC501A detector

The TAC spectra of the small BC523A and an unloaded liquid scintillator BC501A were compared for verification of the capture-gated neutron spectroscopy technique. The two liquid scintillators have the same volume (~ 105 cm³). When compared to the results obtained for small BC523A, there was no true coincidence observed in the TAC spectrum of the BC501A as shown in Figure 4-14. In both spectra, the acquisition time was the same (61,900 s) and the SCA for scatter and capture were set at the values used for the optimum TAC spectrum given in Table 4-2.
Figure 4-14  Comparison between the time difference distribution obtained using small BC523A (upper) and BC501A (lower).

4.6 Large BC523A data

4.6.1 Optimising TAC spectra

Using the trigger circuitry of Figure 4-2, TAC spectra are acquired on an MCA at different SCA windows settings as shown Figure 4-15(a), (b), (c), and (d) in order to optimise the SCA for best TAC spectrum. These typical examples demonstrating optimisation of SCA settings and its corresponding FOM for best TAC spectra are presented in Table 4-4.
Figure 4-15  TAC spectra at different SCA settings.

Table 4-4  Optimisation of SCA settings using FOM for best TAC spectra. The data shown is for the large volume BC523A detector

<table>
<thead>
<tr>
<th>Spectrum</th>
<th>SCA1</th>
<th>SCA2</th>
<th>A/t (c/s)</th>
<th>B/t (c/s)</th>
<th>FOM</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Low TFA gain (25x)</td>
<td>High TFA gain (250x)</td>
<td>(scatter pulse)</td>
<td>(capture pulse)</td>
<td></td>
</tr>
<tr>
<td>(a)</td>
<td>E = 0.5 V</td>
<td>E = 0.4 V</td>
<td>44.7</td>
<td>12.5</td>
<td>3.6</td>
</tr>
<tr>
<td></td>
<td>ΔE = 4 V</td>
<td>ΔE = 2 V</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(b)</td>
<td>E = 0.5 V</td>
<td>E = 0.5 V</td>
<td>30.9</td>
<td>10.6</td>
<td>2.9</td>
</tr>
<tr>
<td></td>
<td>ΔE = 4 V</td>
<td>ΔE = 1.8 V</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(c)</td>
<td>E = 1 V</td>
<td>E = 0.5 V</td>
<td>18.0</td>
<td>4.9</td>
<td>3.7 (optimum)</td>
</tr>
<tr>
<td></td>
<td>ΔE = 3 V</td>
<td>ΔE = 1.8 V</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(d)</td>
<td>E = 1.5 V</td>
<td>E = 0.5 V</td>
<td>11.2</td>
<td>3.3</td>
<td>3.4</td>
</tr>
<tr>
<td></td>
<td>ΔE = 10 V</td>
<td>ΔE = 1.8 V</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The spectrum (c) in Figure 4-15 is the highest in terms of true/chance coincidence and has no overlap between the scatter and capture pulses, thus it was used for capture-gated neutron spectroscopy measurements. Figure 4-16 shows this optimum spectrum in terms of time.
difference between the scatter and the capture pulses, where the three characteristic regions that were previously described in section 4.5.1 are indicated by the arrows. The count rate in the true coincidence region was used to estimate the intrinsic efficiency $\epsilon_i$ of the capture-gated neutron spectrometer exposed to Am-Be neutron source, which is enhanced by using the large BC523A cell. Due to the larger detector side facing the source (10cm x 10cm), the rate of neutrons incident on the detector surface area was calculated to be 2600 neutrons/s, and hence using Equation 2-48 the system had an intrinsic efficiency for fast neutrons of $\sim 0.7\%$, which is a factor of 7 greater than that of the small BC523A cell.

![Time difference distribution of the double pulse events](image)

**Figure 4-16** The time difference distribution of the double pulse events.

### 4.6.2 Mean capture time

The TAC spectrum was re-plotted after logging it and subtracting the background chance coincidence (i.e. a constant value equal to the background counts at channel number 2000). Consequently, a straight line at the true coincidence region results (Figure 4-17). With linear
regression applied to this data, the gradient was used to measure the mean capture lifetime of thermal neutrons in BC523A as 470±80 ns. This value is consistent with both the calculated value given in Table 4-3 and the measured mean capture time using the small BC523A cell, which confirms that the mean capture time is determined solely by the concentration of the $^{10}$B in the liquid scintillator.

![Graph showing mean capture time](image)

**Figure 4-17** The distribution of the time differences between the first and the second pulse of the double event after subtraction of chance coincidence background events in the large BC523A cell. The mean neutron capture lifetime is calculated by linear regression of this data (Jastaniah and Sellin 2003).

### 4.6.3 Digital fast neutron amplitude spectra

Fast neutron amplitude spectra were obtained directly from the amplitude of the digitised neutron moderation pulse within each capture-gated double pulse sequence as shown in Figure 4-18. With the digitiser at a low gain (full scale of 5 V and trigger of 0.2 V), a simple digital pulse height algorithm was used to measure the amplitude of the pulses, which used a binomial smoothing filter to reduce signal noise. An additional SCA (set at E=3.4 V and $\Delta E=0.6$ V) was applied to the TAC output signal (Figure 4-2) so that the waveform digitiser
was only triggered by TAC signals that fall within the true coincidence region of the TAC spectrum. Thus, the gated-TAC spectrum obtained has minimal chance coincidence events (the effect of this additional SCA is described in more details in section 4.6.4). The threshold shown at the beginning of each spectrum in Figure 4-18 is due to the scatter SCA1 (low gain) setting, where the optimised setting is shown in Table 4-4. Lower threshold values could not be reached due to the overlap that will occur between the capture SCA2 (high gain) and the scatter windows, which in turn increases the chance coincidence events.

![Figure 4-18](image)

**Figure 4-18** The pulse height distribution of fast neutrons triggered by the selected window at the true coincidence region on the TAC spectrum. The detailed arrangement of each case is described in Table 4-5.

In Figure 4-18 four spectra are shown, which correspond to the four setup cases described in Table 4-5. In the case 1; the Am-Be source in the water tank produces fast and thermal neutrons that were allowed to reach the detector without interaction in the water by using a hollow tube (Figure 3-8). Contributions to the measured spectrum in this case from gamma
rays produced from the source and as a result of interactions in the water tank and surrounding materials were also possible. In the case 2, the tube was covered from its top end (between the source and the detector) with ~ 2 mm thick cadmium sheet, thus only fast neutrons and gamma rays reach the detector and the event rate drops down to 15 c/s due to the lack of thermal neutrons contribution to the spectrum. In the case 3, the tube was removed hence thermal neutrons became the major affecting radiation and the TAC spectra event rate drops dramatically to 3.7 c/s. In the case 4, the detector was irradiated with a mixture of gamma rays ($^{241}$Am, $^{57}$Co and $^{137}$Cs) and was placed away from the neutron source, which results in almost no TAC spectrum.

<table>
<thead>
<tr>
<th>Case</th>
<th>Setup and coincidence requirements</th>
<th>Events</th>
<th>Rate (c/s)</th>
<th>$\varepsilon_1$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Am-Be source With tube TAC trigger (1)</td>
<td>11,974</td>
<td>20</td>
<td>0.8</td>
</tr>
<tr>
<td>2</td>
<td>Am-Be source Tube with cadmium sheet TAC trigger (1)</td>
<td>8,890</td>
<td>15</td>
<td>N/A</td>
</tr>
<tr>
<td>3</td>
<td>Am-Be source No tube TAC trigger (1)</td>
<td>2,217</td>
<td>3.7</td>
<td>N/A</td>
</tr>
<tr>
<td>4</td>
<td>Mixed gamma ray sources TAC trigger (1)</td>
<td>522</td>
<td>0.9</td>
<td>N/A</td>
</tr>
</tbody>
</table>

It was of interest to show the digital spectrum from the TFA signal with no external trigger applied to the digitiser for comparison with case 1 in Figure 4-18. The obtained spectrum is shown in Figure 4-19, where the same acquisition time (600 s) and the digitiser gain setting (full scale of 5 V and trigger of 0.2) of case 1 were used. The beginning of the spectrum shows the effect of the threshold of 0.2V set on the digitiser. At higher neutron energies a saturation peak is observed due to neutrons with energies (amplitudes) measured above the digitiser full scale. In general, the two spectra of case 1 and the one shown in Figure 4-19 show similarity in terms of their distribution features, but it is not possible to perform a direct comparison of the counts because the latter spectrum is a rate-limited by the digitiser. It is also worth mentioning here that it was not possible to calibrate the x-axis of these spectra in terms of absolute neutron energy due to the lack of a monoenergetic neutron beam and not knowing the relative variation in light sensitivity versus neutron energy.
However, an approximate estimation of the neutron energy range covered by the spectrum (case 2) in Figure 4-18 can be calculated based on the electron-equivalent photon calibration of the large BC523A detector (Table 3-4) and the detector response to the charged particles produced from the $^9$B(n, $\alpha$)Li that have a total energy of $\sim 2.8$ MeV but only show a peak at $\sim 60$ keV. Therefore, the fast neutron energy suggested is $\sim 500$ keV up to $\sim 2.5$ MeV.

![Energy spectrum from TFA signal at low gain setting.](image)

**Figure 4-19**  Energy spectrum from TFA signal at low gain setting.

### 4.6.4 Digital spectra due to gated-TAC output

In the previous section (4.6.3), it was mentioned that an additional SCA gated the TAC output signal, this was done so that the TAC spectrum contains only events that falls within the true coincidence region of the time difference distribution. Using the capture-gated neutron detection circuit (Figure 4-2) with the optimum setting (Table 4-4), TAC spectra due to different settings of the SCA (small, medium and large windows) that gated the TAC were acquired as demonstrated by typical examples shown in Figure 4-20. Consequently, a minimal chance coincidence events contribution to the digital neutron energy spectrum was achieved.
The effect of the gated-TAC signal on the digital spectra is demonstrated in Figure 4-21. Too large or too small windows can greatly influence the digital neutron energy spectrum by changing the event rate as shown in Table 4-6. The high event rate in the case of large window does not mean it is the optimum window setting because other events are contributing to the spectrum together with the true coincidence such as the chance coincidence.
Figure 4-21  Energy spectra from the digitiser at different SCA settings.

Table 4-6  Optimising SCA at TAC output. The acquire time was 600s in each case.

<table>
<thead>
<tr>
<th>Window Size</th>
<th>SCA setting</th>
<th>Events</th>
<th>Rate (c/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Large</td>
<td>E=3.4 V, ΔE=1.8 V</td>
<td>22,164</td>
<td>37</td>
</tr>
<tr>
<td>Small</td>
<td>E=3.4 V, ΔE=0.2 V</td>
<td>4,791</td>
<td>8</td>
</tr>
<tr>
<td>Optimum</td>
<td>E=3.4 V, ΔE=0.6 V</td>
<td>11,974</td>
<td>20</td>
</tr>
</tbody>
</table>

4.7 Coincidence with gated-BGO signal

Prior to adjusting the window of the SCA that is used to gate the BGO signal (Figure 4-2), the BGO cell was characterised in terms of its sensitivity to detect gamma rays. A calibration was carried out for the BGO using an analogue pulse processing system, and irradiated with several gamma ray sources (Table 4-7). The calibration data are plotted in Figure 4-22.
Table 4-7 List of \( \gamma \)-ray sources used to calibrate the BGO detector showing photopeak energies.

<table>
<thead>
<tr>
<th>Source</th>
<th>Energy (keV)</th>
<th>Centroid</th>
<th>(+/- \sigma)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^{133})Ba</td>
<td>356</td>
<td>146</td>
<td>30</td>
</tr>
<tr>
<td>(^{22})Na</td>
<td>511</td>
<td>250</td>
<td>25</td>
</tr>
<tr>
<td>(^{137})Cs</td>
<td>662</td>
<td>345</td>
<td>32</td>
</tr>
<tr>
<td>(^{60})Co</td>
<td>1252</td>
<td>705</td>
<td>59</td>
</tr>
<tr>
<td>(^{23})Na</td>
<td>1274</td>
<td>715</td>
<td>30</td>
</tr>
</tbody>
</table>

Figure 4-22 Gamma ray calibration curve of BGO detector, where photpeaks are shown for those sources.

When irradiated with \( \gamma \)-ray sources, the BGO spectral performance shows features that are different from organic scintillators discussed so far in this study i.e. the photopeak can be observed in the BGO energy spectrum (Figure 4-23), therefore indicating the full energy of the photon as described by Equation 2-7.

The BGO detector was then placed over the water tank, and more than one gamma ray has been observed in the energy distribution as shown in Figure 4-24. The possible interactions shown by the peaks and their corresponding energies that are estimated using the above calibration are listed in Table 4-8. Using the SCA, which is connected to the BGO, a window was set tightly around the estimated 478 keV \( \gamma \)-ray (\(E=0.05\) V, \(\Delta E=0.7\) V). It was then used for coincidence with the TAC signal.
Figure 4-23  Spectra due to several gamma ray sources detected by BGO, showing photopeak energies.

Figure 4-24  Spectrum due to Am-Be source in the water tank detected by the BGO. Showing (a) the 478 keV gamma ray from neutron capture in boron, (b) the 2.22 MeV gamma ray from n-p capture, and (c) another higher energy gamma expected to be from carbon interactions.
Table 4-8 Three γ-rays from neutron interactions detected by the BGO, with acquire time of 3600s.

<table>
<thead>
<tr>
<th>No.</th>
<th>Centroid channel</th>
<th>Error (σ)</th>
<th>Net area</th>
<th>BKGD</th>
<th>Possible interaction</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>213</td>
<td>18</td>
<td>17,158</td>
<td>549,989</td>
<td>478 keV γ-ray from neutron capture</td>
</tr>
<tr>
<td>2</td>
<td>1159</td>
<td>50</td>
<td>32917</td>
<td>130,374</td>
<td>2.22 MeV γ-ray from $^1H(n, \gamma)^2H$</td>
</tr>
<tr>
<td>3</td>
<td>2396</td>
<td>95</td>
<td>5024</td>
<td>61,475</td>
<td>6.13 MeV γ-ray from $^{16}O(n, n' \gamma)^{16}O$</td>
</tr>
</tbody>
</table>

The gated-BGO pulse must always be within the master coincidence range (a window of typically 2 µs) every time a coincidence of the type (1) + (2) in Figure 4-2 occurs i.e. between the TAC output and the BGO. Because they were mostly 0.5 µs out of phase, a delay was added to the TAC output signal (1) and the corresponding signals were in phase all the time as shown by the example given in Figure 4-25.

Figure 4-25 The two input signals (TAC + BGO) in coincidence. To ensure input signals are within the output coincidence window, the output of the coincidence unit triggered inputs.

With the BGO calibrated and the SCA adjusted, additional coincidence requirements to that shown in Table 4-5 may be performed. In Table 4-9 cases 5 and 6 are described. The
BGO output signal was put into coincidence with the TAC output signal via a Master coincidence unit, and the resultant spectrum is shown in Figure 4-26. The SCA connected to the BGO was set at a window around the 478 keV gamma ray (E=0.1 V and ΔE=0.7 V). The TAC spectra were acquired twice in this case i.e. with and without the tube, where low number of events measured in each case limited by the multi coincidence requirements on the detection system. However, the spectrum obtained becomes more purely due to fast neutron events.

Table 4-9  The effect of more coincidence requirements on the digital energy spectrum. The acquisition time was 600s in each case, and the digitiser used at low gain.

<table>
<thead>
<tr>
<th>Case</th>
<th>Setup and coincidence requirements</th>
<th>Events</th>
<th>Rate (c/s)</th>
<th>ε₁ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>Am-Be source</td>
<td>1390</td>
<td>2.3</td>
<td>0.1</td>
</tr>
<tr>
<td></td>
<td>With tube</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Master trigger (1)+(2)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Am-Be source</td>
<td>192</td>
<td>0.3</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td>No tube</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Master trigger (1)+(2)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 4-26  Energy spectra with two coincidence requirements (1) + (2)
4.8 Simulation data

Due to the very low event rate recorded in the small volume BC523A cell when used in the capture-gated neutron detection mode, a Monte Carlo code MCNP-4C (Briesmeister 2000) was used to model the performance of a larger volume BC523A detector that was designed to achieve a higher event rate recorded when used in this low efficiency neutron detection mode. MCNP also modelled the expected performance of the detector-source combination (Figure 3-8) in order to validate the capture-gated neutron spectroscopy experimental measurements.

In order to generate fast neutrons, a hypothetical neutron source was used with energy distribution given by the histogram shown in Figure 3-7, which modelled the energy distribution of neutrons emitted from an Am-Be source (Geiger and Van Der Zwan 1975). Fast neutrons produced from the modelled Am-Be source have a simplified distribution that are grouped in equal energy bins of 0.5 MeV for neutrons up to 8 MeV with different number of neutrons emitted having a maximum at 4-5 MeV. An input data file (Appendix A.2) describes in more details the source specification and shows schematics of the detector-source geometry obtained by MCNP to examine the accuracy of the data entries.

Simulation data reported in the output file (Appendix A.2) are summarised in Table 4-10, part (a) shows that in the case of the small volume BC523A detector, 13276 neutrons are incident on the detector from $1\times10^7$ neutrons emitted from the source, while 42247 neutrons are incident on the large BC523A detector from the same number of neutrons generated from the source. Hence, the simulation indicated that the number of neutrons irradiating (radiation tracks entering the detector surface area) the large BC523A detector showed an increase by a factor ~3 over the small volume BC523A cell, this confirms the observed enhancement of the intrinsic detection efficiency of fast neutrons using capture-gated neutron detection.

Table 4-10 part (c) reveals very important information about the feasibility of detecting the 478 keV γ-ray (from neutron capture in $^{10}$B) in BC523A detectors, where MCNP suggested a high possibility (9607 photons) of releasing the 478 keV γ-ray from neutron capture inside the large BC523A scintillator material, and only lower possibility (2471 photons) when using the small BC523A due to less neutron capture events. In the case of the unloaded liquid scintillator BC501A, a very small number (1093 photons) of photons are released. Thus, it can be concluded that this is obviously due to absence of boron.
Table 4-10 Simulation data using MCNP-4.

<table>
<thead>
<tr>
<th>Scintillation detector cell</th>
<th>BC523A (105 ml)</th>
<th>BC523A (685 ml)</th>
<th>BC501A (685 ml)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a) Radiation tracks entering the scintillation detector</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Neutrons</td>
<td>13,276</td>
<td>42,247</td>
<td>44,534</td>
</tr>
<tr>
<td>γ-rays</td>
<td>8,192</td>
<td>32,337</td>
<td>32,248</td>
</tr>
<tr>
<td>Electrons</td>
<td>90</td>
<td>380</td>
<td>384</td>
</tr>
<tr>
<td>Σ Radiation tracks</td>
<td>21,558</td>
<td>74,957</td>
<td>77,156</td>
</tr>
<tr>
<td>(b) Radiation tracks entering the water tank</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Neutrons</td>
<td>20,189,151</td>
<td>20,192,059</td>
<td>20,200,937</td>
</tr>
<tr>
<td>γ-rays</td>
<td>745,870</td>
<td>750,611</td>
<td>747,734</td>
</tr>
<tr>
<td>Electrons</td>
<td>12,741</td>
<td>12,792</td>
<td>12,794</td>
</tr>
<tr>
<td>Σ Radiation tracks in water</td>
<td>20,947,762</td>
<td>20,955,462</td>
<td>20,961,465</td>
</tr>
<tr>
<td>(c) Photons produced as a result of neutron collisions</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>In scintillator</td>
<td>2,471</td>
<td>9,607</td>
<td>1,093</td>
</tr>
<tr>
<td>In water</td>
<td>9,118,353</td>
<td>9,119,220</td>
<td>9,120,226</td>
</tr>
<tr>
<td>(d) Intrinsic detection efficiency of scintillation detector</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Σ Pulses</td>
<td>11,202</td>
<td>42,665</td>
<td>33,367</td>
</tr>
<tr>
<td>$\epsilon_i = \frac{\sum \text{Pulses in spectrum}}{\sum \text{Radiation tracks}}$</td>
<td>~ 52%</td>
<td>~ 57%</td>
<td>~ 43%</td>
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The proton recoils intrinsic efficiency is strongly a function of hydrogen concentration in the scintillator material, thus efficiencies for both the large and the small volumes BC523A scintillation detectors are expected to be similar. This was confirmed by the simulation data (52% and 57%) shown in Table 4-10 part (d). However, it was lower (43 %) in the case of the unloaded liquid scintillator BC501A, which is due to lower Hydrogen concentration in this scintillator material (Bicron).

MCNP plotted pulse height distributions (Figure 4-27) of the three different scintillation detectors i.e. the unloaded liquid scintillator BC501A (a), the large volumes BC523A (b) and the small volume BC523A (c). The deposited pulses in each scintillation detector are due to interactions from the mixed field of neutrons and γ-rays.
Figure 4-27  The energy distribution of proton recoil and gamma ray events incident on (a) the unloaded liquid scintillator, (b) the large BC523A detector, and (c) the small BC523A detector, where the number of events in the large volume BC523A scintillators is higher by a factor of 3 over the small volume BC523A cell.
Fast neutron collisions with hydrogen in the scintillator material produced proton recoils that deposited their energy in the scintillator material, and provided energy distributions with a clear feature that is dominated by organic scintillator's response function that was described by Figure 2-16. For the collision of a fast neutron of 4-5 MeV with hydrogen, the average proton recoil energy is about half of this value. This is consistent with the data demonstrated in Figure 4-27.

There are also considerable amounts of γ-rays (Figure 4-28) produced from the interactions of neutrons in the water tank (Figure 3-8) e.g. 2.22 MeV γ-ray from \(^1\text{H}(n, \gamma)^1\text{H}\), and interactions in the scintillation detector e.g. 478 keV γ-ray from neutron capture in boron. Such γ-rays contribute to the energy distributions shown in Figure 4-27. For the design of a capture-gated neutron spectrometer with less chance coincidence, the detection of the 478 keV γ-rays was of most interest. Fortunately, it was observed in both BC523A spectra plotted by MCNP, but more obviously in the large volume BC523A detector as indicated by the arrows in Figure 4-27 (b). Therefore, γ-ray spectroscopy was included in the design of the large volume BC523A cell using a BGO scintillation detector.

![Figure 4-28](image.png)  
**Figure 4-28** The distribution of gamma rays produced from the Am-Be source interactions with materials such as water and scintillators.
4.9 Discussion

In this chapter, the use of digital data acquisition techniques for capture-gated neutron spectroscopy using BC523A detectors of two different volumes has been investigated. When irradiated with fast neutrons produced from an Am-Be neutron source, the measured mean neutron capture time was ~ 0.5 µs in both detectors. This is a factor of ~ 5 shorter time than that reported for liquid scintillator loaded with natural boron. The capture-gated detection efficiency of the small BC523A (105 cm$^3$) scintillator cell was limited, and the extension of this technique to a large volume BC523A (685 cm$^3$) detector head suitable for use in portable dosimeter systems has also been discussed in this chapter. The increase in volume by a factor of 6.5 between the two cells produced an increase in the capture-gated coincidence rate by a factor of 38. Consequently, a neutron detection efficiency enhancement (a factor of ~ 7 higher) was achieved using the larger volume BC523A. Due to the less scintillator volume in the small volume BC523A cell, multiple fast neutron scattering followed by neutron capture was found to be unlikely the case. The majority of the recorded double-pulse sequences were due to cases where the neutron loses all of its kinetic energy in a single collision followed by neutron capture of the diffused thermal neutron this explains why a low count rate was observed when using the small BC523A.

Compared to previously developed capture-gated neutron spectrometers that uses large volumes (typically few litres) of organic scintillator materials e.g. 3700 cm$^3$ of BC454 (Feldman 1991) and 7900 cm$^3$ of BC454 (Miller, Biddle et al. 1999), this work has an advantage of performing a capture-gated neutron detection at a reasonable double pulse event rate with only ~ 700 ml of BC523A scintillator material.

The simulation using MCNP provided useful information in selecting the suitable size of the larger liquid scintillator cell. The code modelled the expected enhancement in terms of the event rate interacting in the two cells of different volumes and shapes, and clear enhancement (a factor of 3 in terms of event rate incident on the detector) has been achieved which increased the neutron detection efficiency.

Using the developed capture-gated neutron detection system, a double pulse capture-gated neutron event sequence was observed on a digital oscilloscope, which was taken from the low gain TFA signal. The digital capture of this double pulse sequence was shown to be a powerful technique to acquire both the time-stamped pulse amplitudes and the capture
lifetime in a single data set. Consequently, it was possible to obtain the energy (in arbitrary units) of the incident fast neutron from the amplitude of the first pulse using a simple digital pulse height algorithm. Additionally, the developed system offers the possibility of digitally capturing the pulse shape and allowing the use of soft-ware based PSD algorithm as presented in chapter 3, which will further eliminate chance coincidence (gamma-neutron coincidence) events that may produce a valid but actually false TAC output.

Using the simulation code, it was also possible to observe the 478 keV gamma ray in the energy spectrum. Therefore, gamma ray spectroscopy was included in the design of the large BC523A head. The 478 keV gamma ray event was detected by a BGO and employed in adding a further coincidence requirement to the original capture gated circuitry (Figure 4-1), so it was modified (Figure 4-2) to include this additional requirement. However, the gamma ray background underlying the 478 keV gamma ray was so intense that it was not possible to efficiently eliminate them using the SCA that gated the BGO signal alone, but when the detection system worked with all its coincidence requirements together, this effect was reduced and a better gamma ray filtering was achieved.

In the capture-gated neutron spectroscopy mode (Figure 4-2), the TAC trigger circuit is designed to operate with optional coincidence requirements (1) or (1) + (2), thus achieving two levels of digital fast neutrons spectrum in terms of eliminating false TAC output. However, since the rate of capture-gated events is much smaller than that of a single photon or neutron event due to small size cells used in this work, this multi coincidence requirement comes at the expense of the recorded event rate and consequently the detection efficiency. With the capture-gated trigger circuit in coincidence with the BGO signal, the count rate was greatly reduced (2.3 cs').

The key to the enhanced capture-gated spectroscopy is the delayed capture of the thermalised neutron in $^{10}$B that has a time correlated occurrence with the energy signal from proton recoils. The measured mean capture lifetime in BC523A was used for correct setting of the timing logic of the spectrometer thus obtaining good neutron detection efficiency with a low chance coincidence rate.
Chapter 5 Conclusion

The availability of high speed waveform digitisers allowed new techniques for neutron and gamma ray discrimination using fast organic scintillators. The performance of 1 ns sampling time, 8-bit resolution, digitisers has been successfully demonstrated. Good n/gamma PSD has been demonstrated using computationally-simple digital pulse rise time algorithms. When the digital pulse processing was used to investigate the PSD properties of BC523A, first tests with an 8-bit, 1 GS/s waveform digitiser (500MHz flash ADC) have produced acceptable pulse height and rise time information from the detector. Using only simple pulse processing algorithms, clear pulse shape discrimination was achieved between fast neutron and gamma ray interactions in the detector with measured FOM of 1.2 at low gain setting. Compared to unloaded liquid scintillator (BC501A) with FOM of 1.5 at low gain setting, the loading element (°B) did not significantly reduce the PSD capability at low gain settings. At high gain setting however, poor pulse shape discrimination between gamma events and thermal neutrons was observed as expected from BC523A (Aoyama, Honda et al. 1993). In contrast, BC501A provides PSD capability even at high gain setting. Furthermore, the achieved PSD in BC501A (FOM of 1.5) using only an 8-bit ADC was found comparable with the PSD in BC501A (FOM of 1.6) obtained using a 10-bit, 50MHz flash ADC as previously reported (Jordanov and Knoll 1995). The author strongly recommends exploring ways to enhance the technique, and investigate further digital PSD algorithms for use with organic scintillator detectors. These techniques have potential applications in neutron monitors where event-by-event n/γ discrimination are required.

For capture-gated neutron detectors, digital capture of the double pulse sequence is a powerful technique to acquire both the time-stamped pulse amplitudes and the capture lifetime in a single data set. The energy of the incident fast neutron was directly measured from the amplitude of the first pulse using a simple digital pulse height algorithm. Additionally, digital capture of the detector full pulse shapes allows the use of software-based PSD algorithms to further eliminate chance coincidence events that could have produced a valid TAC output. The achieved digital PSD capability using BC523A allows its use effectively with the developed spectrometer, which has potential application for capture-gated neutron monitors.
A fast neutron spectrometer was developed using a 105 cm\(^3\) BC523A commercial cell. Clear evidence of the capture-gated neutron detection mode has been observed. The measured neutron capture lifetime was \(\sim 0.5\) µs. This value is consistent with that expected from this material using published cross section values. Due to the relatively high concentration of \(^{10}\)B in BC523A, the neutron capture lifetime achieved using this material is approximately five times shorter than that of natural-boron loaded liquid and plastic scintillators, which has advantages in terms of reduced chance coincidence events and a higher true count rate capability. The low event rate (0.47 cs\(^{-1}\)) and consequently the neutron intrinsic detection efficiency (0.1 %) observed for this detection mode is to be expected from a small scintillator cell. Therefore, a second phase of this work was carried out to extend the capture-gated neutron spectroscopy measurements to a larger volume (685 ml.) BC523A cell. This larger cell produced a higher count rate of (18 cs\(^{-1}\)) and hence a neutron detection efficiency enhancement (0.7 %) in the capture-gated mode.

The developed fast neutron spectrometer provides an incident neutron energy spectrum that can in principle allow the determination of the neutron dose equivalent. However, this requires further work to calibrate the detector using a monoenergetic neutron beam. Additionally, the spectrometer can also be adapted to improve the chance coincidence rejection by adding a further coincidence requirement using the gated BGO signal. However, this results in significant reduction in overall detection efficiency caused by the BGO coincidence, which makes this configuration unsuitable for a practical dosimeter.

While developed specifically for capture-gated neutron spectroscopy, this digital spectrometer has other potential applications for high sensitivity neutron detection, for example in radiation physics (e.g. neutron flux and dose in boron capture neutron therapy) and security applications (e.g. detection of illicit nuclear materials). Digital PSD has been shown to be a powerful technique for the capture and analysis of complete waveforms on event-by-event bases for fast and slow neutrons and gamma rays. The sampling rate of 1GS/s used in this work was among the highest available speeds at the time of the beginning of this research (2000), although there is now the potential to extend this technique with the very recently available sub-nanosecond waveform digitisers. Replacing the analogue triggering circuit with a digital one could also be a future work that aims to introduce a compact system to operate within radiation environment e.g. accelerators. The author anticipates that the fast neutron detector will be a significant improvement over existing detectors, particularly in the measurements of a wide range of neutron fluxes in a high gamma background.
BIBLIOGRAPHY


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Bicron "http://www.bicron.com".


Varian "http://www.varianinc.com".


Appendices

A.1 Calculation of scintillation efficiency using XCOM:

This example calculates the intrinsic detection efficiency for different inorganic and organic scintillators as a function of γ-ray energy up to 10 MeV. Curves due to different inorganic and organic scintillators of 10 cm thick are shown in Figure A-1 and Figure A-2 respectively, using a mass attenuation coefficient supplied by a web program (XCOM). The curves show that in general, the efficiency decreases with higher energies but differs from one type of scintillator to the other. The efficiency curve for a 3cm BGO detector was also plotted.

![Figure A-1](image1.png)

**Figure A-1** The detection efficiency for different inorganic scintillators as a function of energy.

![Figure A-2](image2.png)

**Figure A-2** The detection efficiency for different organic scintillators as a function of energy.

A.2 Monte Carlo simulation data using MCNP-4C

Small volume BC523A cell

```
1mcnp
version 4c
n=small
1.  C cell cards
2.  1.1 -1.0 -2.3 4 -5.6 (-7:8) $ Water tank
3.  2 2 -0.916 -9 $ Liquid scintillator cell
4.  3 3 -0.000129 -10 @1 #2 (-7 -10 9 -8) $ Air + Hollow of air
5.  4 0 10 $ Outside world
6.
7.  C surface cards
8.  1 PY 25.5
9.  2 PY -50.5
10.  3 PZ 34.5
11.  4 PZ -31.5
12.  5 PX 48
13.  6 PX -48
14.  7 PZ 0
15.  8 CZ 2.6
16.  9 RCC -2.6 0 57 5.2 0 0 2.6
17.  10 SO 100
18.
19.  c Transport mode
20. Mode N P E $ Transport neutron, photons and electrons
21. IMP: N 1 1 1 0 $ Neutron importance in each region
22. IMP: P 1 1 1 0 $ Photon importance in each region
23. IMP: E 1 1 1 0 $ Electron importance in each region
24. c radius=1cm. length=2 cm
25. SDEF erg=d1 pos=0 0 0 cell=1 rad=d2 ext=d3 axs=0 1 0 vec=0 1 0 dir=d4
26. s11 H 0 0.5 1 1.5 2 2.5 3 3.5 4 4.5 5 5.5 6 6.5 7 7.5 8
27. sp1 0 0 10.8 6.8 5.2 6.8 12.8 14.8 12.8 12.8 14.8 12.8 14 9.2 7.2 5.6 7.2 7.6
28. s12 0 0.1 $ Source radius sampling
29. s13 2 $ Source length sampling
30. sb4 -31 1.5 $ Biasing applied to source dir parameter
31. F8:E 2 $ Electron energy deposited in region 2 (distribution of pulses)
32. EB 0.1e-5 1e-3 3201 $ Histogram energy into bins (1=integer) 0-8 Mev
33. FTB GEB -0.00244 0.092 0
34. MPLb
35. M1 1001 0.667 8016 0.333 $ Water
36. M2 1001 0.558 6012 0.321 8016 0.091 5010 0.027 5011 0.003 $ BC523A
37. M3 7014 0.8 8016 0.2 $ Air
38. NPS 10000000 $ Histories before termination.
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tally for photons electrons
this tally is modified by ft geb

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5.9906E-01 1.47286E-06 0.1730 9.9776E-01 9.3461E-07 0.4702
6.2398E-01 9.85408E-07 0.1730 1.0227E+00 7.10161E-07 0.4376

137
Large BC523A cell

1mcnp    version 4c

n=large

 1-  C cell cards
    1 1 -1.0 1 -2 -3 4 -5 6 (-7:8) $ Water tank
    2 2 -7.13 -9 -11 12 $ BGO scintillator
    3 3 -0.916 -10 -13 14 #1 #2 $ BC523A liquid scintillator
    4 4 -0.000129 #1 #2 #3 -15 :(7 9 -8 -15 10) $ Air + Hollow of air
    5 0 15 $ Outside world

 2-  C surface cards
    1 7 PZ  25.6
    2 2 PY -50.5
    3 3 PZ  34.5
    4 4 PZ -31.5
    5 5 PX  48
    6 6 PX -48
    7 7 PZ  0
    8 8 CZ  2.6
    9 9 c/x 0 57.5
    10 10 c/x 0 57 5
    11 11 px 5
    12 12 px .5
    13 13 px 5
    14 14 px -5
    15 15 SO 100

 3-  c Transport mode
    Mode N P E $ Transport neutron, photons and electrons
    IMP:N 1 1 1 1 0 $ Neutron importance in each region
    IMP:P 1 1 1 1 0 $ Photon importance in each region
    IMP:E 1 1 1 1 0 $ Electron importance in each region

 4-  c radius=1cm, length=2 cm

 5-  SDEF erg=d1 pos=0 0 0 cel=1 rad=d2 ext=d3 axs=0 1 0 vec=0 1 0 dir=d4

 6-  sli H 0 0.5 1.5 2.5 3.5 4 4.5 5 5.5 6 6.5 7 7.5 8

 7-  sp1 0 0 10.8 6.8 5.2 6.8 6.8 7.7 8 14.8 12 8 12 8 12 14 4 12 9.2 12 7.2 7.2 7.2 7.6

 8-  sli 0 1 $ source radius sampling

 9-  sli 3 2 $ source length sampling

10-  sb4 -31 1.5 $ Biasing applied to source dir parameter

11-  FBE:E 3 $ Electron energy deposited in region 3 (distribution of pulses)

12-  EB 0 1e-5 1e-5 3201 8 $ Histogram energy into bins(i=integer) 0-8 Mev

13-  FTE:GE 8 0.00244 0.092 0

14-  MPLT

15-  MI 1001 0.667 8016 0.333 $ Water (Mn ZAID= FRACTION= etc)
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Summary of photons produced in neutron collisions per cell:

- Photon energy per source neut.
- Avg. photon energy per source neut.
- Weight/ neut.
- Neutron collision energy/mev/ gpm per photon.
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<th>number of photons</th>
<th>cum number of photons</th>
<th>weight of photons</th>
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Itally 8 tally type B pulse height distribution. units number

tally for photons electrons
this tally is modified by ft geb

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141
Unloaded BC501A cell

1mcnp version 4c

n=bc501a

C cell cards
1. 1 -1.0 -1.2 -3 4 -5 6 (-7:8) $ Water tank
2. 2 2 -7.13 -9 -11 12 $ BGO scintillator
3. 3 3 -0.874 -10 -13 14 $ BC501A liquid scintillator
4. 4 4 -0.000129 #1 #2 #3 -15 $ Air + Hollow of air
5. 5 0 15 $ Outside world

C surface cards
1. 1 PY 25.5
2. 2 PY -50.5
3. 3 PZ 34.5
4. 4 PZ -31.5
5. 5 PX 48
6. 6 PZ -48
7. 7 PZ 0
8. 8 CZ 2.6
9. 9 c/x 0 57 1.5
10. 10 c/x 0 57 5
11. 11 px 5
12. 12 px -5
13. 13 px 5
14. 14 px -5
15. 15 S0 100

C Transport mode
Mode N P E $ Transport neutron, photons and electrons
IMP:N 1 1 1 1 0 $ Neutron importance in each region
IMP:P 1 1 1 1 0 $ Photon importance in each region
IMP:E 1 1 1 1 0 $ Electron importance in each region

C radius=1cm, length=2 cm
SDEF erg=d1 pos=0 0 0 cell=1 rad=d2 ext=d3 axs=0 1 0 vec=0 1 0 dir=d4
S1 H 0 0.5 1.5 2.5 3.5 4.5 5.5 6.5 7.5 8
S1I D 0 10.8 6.8 5.2 6.8 12.8 14.8 12.8 12.8 14.1 12 9.2 7.2 5.6 7.2 7.6
S12 D 0 1 $ source radius sampling
S13 2 $ source length sampling
Sb4 -31.5 $ Biasing applied to source dir parameter
F8:E 3 $ Electron energy deposited in region 3 (distribution of pulses)
E8 0 1e-5 1e-3 3201 8 $ Histogram energy into bins(1=integer) 0-8 Mev
FT5 GEB -0.00244 0.092 0
WPLT
W1 1001 0.667 8016 0.333 $ Water (Mn ZAID FRACTION1 .. etc).
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Itally tally type 8 pulse height distribution. tally for photons electrons this tally is modified by ft geb

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145
Geometry plots

The numbers shown in the geometry plots specify different cells numbers and surfaces that were described in the input file. Different projections allow viewing the cells from several directions.

1. Small BC523A cell-source arrangement:

Figure A-3  Geometry at plane y=0, origin 0 0 0 and frame=100x100 cm.
Figure A-4  Geometry at plane x=0, origin 0 0 50 and frame=45x45 cm.

Figure A-5  Geometry at plane y=0, origin 0 0 50 and frame=55x55 cm.
Figure A.7
Geometry at plane x=0, origin 0 0 50 and frame=20x20 cm.

Figure A.6
Geometry at plane y=0, origin 0 0 50 and frame=20x20 cm.
2. Large BC523A cell-source arrangement:

**Figure A-8** Geometry at plane y=0, origin 0 0 57 and frame=50x50 cm.

**Figure A-9** Geometry at plane y=0, origin 0 0 57 and frame=10x10 cm.
Figure A-10  Geometry at plane x=3, origin 3 0 57 and frame=35x35 cm.

Figure A-11  Geometry at plane x=3, origin 3 0 57 and frame=20x20 cm.