

Development of scintillator arrangements and coding methods in neutron sensitive ZnS scintillation detectors

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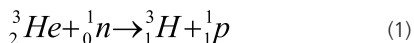
Abstract

ISIS is the world's most powerful pulsed neutron source ^[1]. The neutrons it produces are used to study the structure and dynamics of materials on the atomic and molecular scale. Material characteristics can be determined via diffraction and spectroscopic measurements, usually requiring two types of detector - ones capable of position resolution and ones capable of energy resolution. The Neutron Detector Group is responsible for design and evaluation of the neutron detectors used at ISIS, and as such has an active role in the development of new detection techniques. Presented is the development of a prototype position sensitive thermal neutron detector with potential applications as an alternative to resistive wire proportional counters in single crystal diffraction experiments, as well as low count rate experiments which require high neutron detection efficiency.

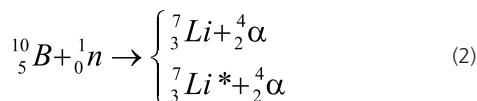
Neutron detection

Thermal (or slow) neutrons are generally defined as neutrons with energies below the cadmium cut-off of 0.5 eV, although the thermal neutrons used at ISIS are typically in the region of 0.05 eV. Unlike other forms of radiation, neutrons do not produce direct ionization which is the basis of most detection mediums. They must be detected indirectly through nuclear reactions, and then

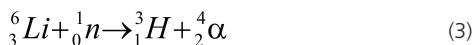
detecting the charged exit channel particles. Three common reactions for neutrons with de-broglie wavelengths of 1 Angstrom are shown below ^[2]:



With a reaction cross section of 2800 barns and a Q value of 0.764 MeV



With a reaction cross section of 2100 barns and Q values of 2.792 MeV (ground state) and 2.310 MeV (excited)



With a cross sections of 520 barns and a Q value of 4.78 MeV

Once a thermal neutron has undergone a reaction, the decay products need to be detected to produce a quantifiable signal. In the case of boron and ³He, this can be done using gas proportional counters (with boron in the form of boron trifluoride). With ⁶Li, the preferred method of detection is to use a scintillator, and use the scintillation light to make a measurable signal. A convenient and relatively inexpensive scintillator that can be mixed with ⁶Li into thin strips is zinc sulphide, ZnS (Ag). Over half of the detectors at ISIS are based on scintillators ^[3], and the ⁶Li/ZnS arrangement was the method of choice for this prototype.

Zinc sulphide has high scintillation efficiency; however it is also opaque to its own luminescence. This means as larger thicknesses are used, the chance of a neutron undergoing a reaction increase, but the chance of detecting the scintillation light created from the decay products of that reaction decrease. This can be partially overcome by angling scintillator strips with respect to the incoming neutrons; this increases the pathlength of the neutrons through the scintillator while maintaining an optimal light collection ^[4].

Strips of ⁶Li/ZnS can be made into an array of pixels by using a series of metal dividers. In its simplest form, each strip of scintillator is surrounded by 4 metal dividers which also act as reflectors (with an additional reflector above the scintillator), this gives a single element which can be viewed by an array of fibre optic cables to detect the scintillation light. To make the element into a set of pixels, additional reflectors can be added perpendicular to the scintillator. Detecting scintillation light in a pixel is slightly more complicated than in an element, instead of using an array of fibres, typically a set of fibres is used in each pixel, the number of which depends on the coding method being used. Scintillation light collected travels along fibre optic cables to Photo Multiplier Tubes (PMT), before being amplified and discriminated.

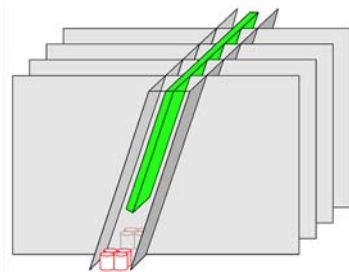


Figure 1. Single scintillator (green) with 4 fibres in each pixel (⁴C_n coding).

Coding involves assigning a unique combination of 2 or more PMTs to elements or pixels. This means that if a sufficiently large signal is produced in a combination of PMTs at the same time, the element or pixel where the neutron interaction that caused that signal is known. In an element, typically arrays of fibres are used that are viewed by two PMTs, with every other fibre going to one of the PMTs, this is known as ²C_n coding. The situation becomes more complex with pixelated detectors as ²C_n coding isn't very efficient due to there only being ⁿC₂ combinations (where n is number of PMTs), and for pixelated detectors higher order codes must be employed.

Prototyping

Simulating detector response:

It was decided to investigate ³C_n coding arrangements within a 5 x 5mm² pixel using two scintillator strips. A common technique used to gauge potential detector design is to run a set of Monte Carlo simulations. The advantage of using Monte Carlo is the ability to optimise detector characteristics before building a prototype. The main characteristics requiring optimising in a scintillator based detector are total collection and variation of light across a pixel. Factors affecting this are number and arrangement of fibre optic cables, distance between fibre optic cables and scintillator, orientation and number of scintillator strips, and pixel dimensions. Total light collected and total variation of light collected were simulated for three types of fibre arrangement (circular, linear, and evenly spaced – with the first two being at the centre of each pixel) at distances of 1, 3, 4, 5, 6, and 7mm's distance from the scintillator. Additional simulations were run to see if adding a diffuse (white) reflector below the bundles of fibre optic cables would increase light collection

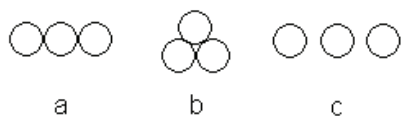


Figure 2. Fibre optic cable arrangements (top down view). Linear arrangement (a), circular arrangement (b), evenly spaced arrangement (c).

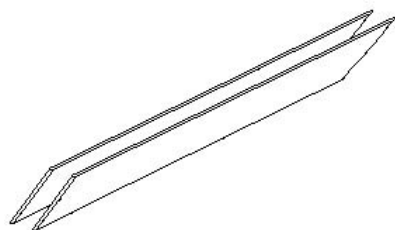


Figure 3. Double scintillator arrangement (shown without reflectors or fibres)

Monte Carlo findings:

In general, total light collected decreased as the fibre optic cables were moved further from the scintillator. At shorter spacings, the response of the detector to neutrons incident at different positions within each pixel showed large degrees of variation. This is undesirable in a real detector because for the need to set thresholds on the size of signal attributed to detection of a neutron. As a consequence only two of the spacings showed minimal variation, and these were at 6 and 7mm's respectively. Similarly, two of the three fibre arrangements showed preferential light variation (circular and linear). Adding a diffuse reflector below the fibre optic cables allowed photons that would have been lost to be reflected back into the pixel where an amount were re-reflected into the fibre optic cables. This gave an increase in total light collection (approximately 10%) without affecting the variation of light collected across each pixel.

Construction and testing:

It was decided to construct small prototypes of the simulated detectors that had promising characteristics. In total 8 variations were tested comprising of:

- Linear and circular fibre optic cable arrangements (incorporated into two different bases)
- 6 and 7mm scintillator to fibre optic cable spacings
- 'Normal' base and base with built in diffuse reflector (the base is also used to hold fibre optic cables in place)

All prototypes were tested on a 370 GBq Americium:Beryllium (Am:Be) neutron source. Sources of this type typically provide in the region of 2.2×10^7 neutrons per second^[5]. The fast neutrons emitted are moderated to thermal energies due to the de-broglie wavelengths of interest for diffraction experiments corresponding to these energies. Each prototype consisted of a linear array of 40 5 x 5mm² pixels. Although this arrangement was divided into pixels, the outputs of each series of fibres were summed to one PMT (3 PMTs in total to represent 3 fibres per pixel) so that the efficiency of each design could be evaluated. The response of each detector was evaluated in two ways. Firstly, the counts per second for a given lower level discriminator (LLD) level were obtained and plotted. Secondly, the intrinsic gamma sensitivity of the detectors were obtained at the same LLD levels using a ⁶⁰Co source (1.173 and 1.332 MeV photons^[6]).

Results

The results for each prototype detector type are summarised in table 1. All detectors showed the same characteristics – as the LLD was decreased the count rate slowly increased linearly before

reaching a small plateau region, and then as the LLD was decreased further beyond this point the count rate linearly increased quickly. The higher count rates beyond the plateau region are likely to be attributed to counting the same neutron event twice caused by the afterglow from the scintillator and due to the intrinsic sensitivity of the detector to gamma photons associated with the Am:Be source as well as any (n, γ) capture reactions associated with the water moderator (2.223 MeV).

All detectors had neutron detection efficiencies above 50% for neutron wavelengths of 1Å with gamma sensitivities of less than 10^{-6} . All detectors using a diffuse reflector (white base) performed better than the black equivalent. Detectors using a 7mm scintillator to fibre spacing performed better than a 6mm, this shows that total light collected isn't always the deciding factor in detector efficiency.

Table 1. Summary of results

Fibre arrangement	Fibre to Scintillator spacing	Base colour	Neutron counts/sec at LLD of 80mV	Neutron detection efficiency (%)	Error (+/-)	Gamma sensitivity	Error (+/-)
Linear	6mm	Black	413	51.6	0.25	2.0E-07	3.E-08
Linear	6mm	White	445	55.6	0.26	1.5E-07	5.E-08
Linear	7mm	Black	460	57.5	0.27	4.0E-07	5.E-08
Linear	7mm	White	472	59.0	0.27	5.0E-07	1.E-07
Circular	6mm	Black	421	52.6	0.26	1.5E-07	5.E-08
Circular	6mm	White	455	56.9	0.27	2.5E-07	1.E-07
Circular	7mm	Black	460	57.5	0.27	2.0E-07	1.E-07
Circular	7mm	White	464	58.0	0.27	2.5E-07	1.E-07

Beamline prototype design

The next stage of prototyping was to design and construct a prototype capable of obtaining diffraction data on the ISIS beamline. For a beamline prototype to be capable of obtaining diffraction pattern data it must have a pixelated detection area, as well as having a more sophisticated housing: this comprises of less housing and thinner materials to minimise scattering of neutrons, and PMTs are also magnetically shielded.

Choosing detector characteristics:

Choosing an initial prototype for construction of a beamline prototype was not only based on neutron detection efficiency, but also on ease of construction. It was decided to construct the beamline prototype using the circular array of fibres instead of the linear, the circular array was only slightly less efficient than the linear, but constructing the array of linear fibres would have required milling components – this is more complicated and expensive than drilling the holes required for an array of circular fibres. A fibre to scintillator spacing of 7mm was chosen for its better detection efficiency, as was using a white base.

Design Considerations:

Neutrons not absorbed in the detection medium initially may be back scattered by other parts of the detector and still be absorbed, although the neutron will more than likely be absorbed in a pixel/element which will not give a true indication of its origin from the sample being studied. It is for this reason that some parts of neutron detectors are made out of neutron absorbing material. Some common neutron absorbing materials are boron carbide (B_4C), cadmium (Cd), and boron nitride (BN). Boron carbide is widely used to build the

housing that the fibre optic cables are in, however B_4C is also a difficult material to machine due to its chemical properties. It was decided to construct the fibre optic cable housing out of boron nitride due to its comparative ease of manufacture and it also has the advantage of being naturally white, which makes it an ideal base.

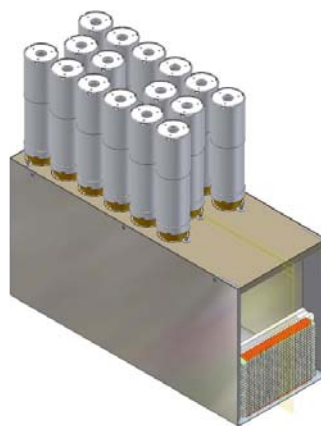


Figure 4: CAD assembly drawing and finished beamline prototype (without PMTs)

Conclusions

A new high resolution, high neutron detection efficiency, 2 dimensional prototype pixelated scintillation detector has been developed for use on the ISIS facility. The specifications of this prototype are a 560 pixel detector with $5 \times 5 \text{ mm}^2$ 2 dimensional resolution, 50% neutron detection efficiency at 1 Angstrom, and a gamma sensitivity of $<10^{-6}$. This prototype will be used as a tool for measuring the performance of resistive wire gas tubes planned for use on the new WISH instrument at ISIS. The WISH magnetic diffractometer is one of 7 day one instruments planned for ISIS target station 2. Due to the single crystal nature of the samples due to be studied on WISH resistive wire gas detectors are currently the preferred choice, however due to the expensive nature of these tubes this prototype may provide an alternative choice. This prototype will also have applications at ISIS for low count rate two dimensional position sensitive detectors requiring 50% neutron detection efficiency at 1 Angstrom. Current scintillation devices of this type typically have 20% efficiency at this wavelength; this prototype will provide a viable alternative for future instruments.

References

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