Scintillating Fiber Technology for a High Energy Neutron Spectrometer

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Overview

Objective: Develop a compact low-power neutron spectrometer that uniquely identifies neutrons in the mixed radiation field expected on crewed deep-space missions.

Secondary neutrons are generated by cosmic rays striking heavy crewed spacecraft as well as lunar and planetary surfaces\textsuperscript{1,2}. It has been shown that secondary neutrons can account for up to 50\% if the total dose-equivalent received by the crew\textsuperscript{3}.

Technical Approach: Use isolated fast and thermal neutron detectors.

Unfold the neutron energy spectrum from the signal recorded in a plastic scintillator. Identify the neutrons using signals from \textsuperscript{6}Li-loaded scintillating glass fibers to detect the neutrons after they have thermalized. Isolate the signals from the two scintillators and detect them separately.


Energy Dependence of the Neutron Quality Factor

Neutrons are thermalized, deposit all their energy in the plastic scintillator via recoil protons and then are captured in a $^6$Li loaded scintillating glass fiber. Produced light is read out at the fiber ends by a Photomultiplier Tube, that generates an event trigger. Scintillation light produced in plastic by recoil protons is collected by separate PMT, which provides a signal proportional to energy that neutron left in plastic scintillator.
**Basic Approach:**

- Design a neutron spectrometer consisting of a block of plastic scintillator to moderate fast neutrons and measure their energy
- Embedded in this block are optically isolated scintillating fibers loaded with a thermal-neutron-capturing isotope which will uniquely detect the thermal neutrons
- Fibers are read out by photomultiplier tubes at two sides and neutron capture triggers are generated by coincidence circuit to minimize false triggers associated with PMT noise.
Spectrometer Design Concept

The choices for the thermal neutron absorbing isotope are:
• $^{10}\text{Be}(n,\alpha)^7\text{Li} + \gamma$ and $^{10}\text{Be}(n,\alpha)^7\text{Li}$ deposits either 2.79 or 2.31 MeV (if $\gamma$ escapes)
• $\text{Li}(n, \alpha)^3\text{H}$ deposits $4.78$ MeV; preferred because the large unique capture signal

The choices for fiber cladding/encapsulation are:
• Commercially available clad fibers have hygroscopic cladding which is soluble in plastic scintillator
• UV curable polymer cladding - UV excited long-lived atomic levels in the glass scintillator
• Teflon-AF – lowest refractive index and chemically inert
• Teflon-AF-clad capillary tubes – Teflon AF advantage + $\alpha$ and $^3\text{H}$ are contained

Choice of Fibers:
• Simulations have shown that 100-150 $\mu$m diameter fibers are the best tradeoff between containing the $\alpha$, $^3\text{H}$ and creating scintillation associated with $\gamma$ rays not large enough to mimic neutron captures
Thermal Neutron Capture Signal in the $^6$Li-loaded Scintillating Glass Fibers

\[
\text{Li} + \text{n} \rightarrow ^4\text{He} (2.105 \text{ MeV}) + ^3\text{H} (2.734 \text{ MeV})
\]

- **Entries**: 80182
- **Mean**: 4.569
- **RMS**: 0.6594

88% of all neutron captures

$^3$H escapes
Pre-Capture Signal in the Plastic Scintillator 10 MeV

Neutron Energy 10 MeV

C(n,\alpha)^7B e

Entries: 1554
Mean: 7.066
RMS: 3.646
Pre-Capture Signal in the Plastic Scintillator 20 MeV

Neutron Energy 20 MeV

C(n,n’)$^3\alpha$

C(n,$\alpha$)$^7$B e

Entries: 1168
Mean: 11.26
RMS: 6.717
Using the Fiber as an Optical Wave Guide

Critical angle for total internal reflection

- \( \sin^{-1}(1.31/1.5258) = 30.8^\circ \)
- 25.3 go to each phototube
- Each tube produces 6.3 photoelectrons
- Threshold = 2 p.e.s or 0.9 MeV
- Estimated efficiency of \( \gamma \)'s to mimic thermal neutron capture signals: \( \sim 10^{-6} \).
Fibers Inserted in Capillary Tubes

Image of Teflon coated fused silica capillary tube (OD=363um; ID=150um) with inserted $^6$Li glass fiber (OD = 100um)

Capillary tube with $^6$Li glass fibers submerged in BC600 optical cement and attached to PMT

Capillary tube with $^6$Li glass fibers in BC600 optical interface
Performance of Fibers Inserted in Capillary Tubes

Am-241 spectrum. Test article consists of Teflon-coated fused silica capillary tubes with inserted $^6$Li glass fibers held in air. Alpha source was attached at the opposite to PMT end of fibers. PMT response was integrated over 160ns. Scale: 200pV*s/div (max =~ 14pe)

Am-241 spectrum. Teflon-coated capillary tubes with inserted $^6$Li glass fibers are submerged in BC600 over 3.0”. Same measurement conditions. 200pV*s/div (max =~ 12pe)
Design Details

• Teflon coated silica glass capillary tubes with inserted $^6$Li-loaded scintillating glass fibers were chosen to detect thermal neutrons
• Capillary tubes additionally serve as an absorber for escaping tritium nucleus in cases when neutron capture occurs at the edge of $^6$Li glass fibers, preventing any scintillation in plastic scintillator associated with neutron capture event
• This feature allows to use plastic scintillator as an anticoincidence detector to further reject gamma rays
• Before casting into plastic resin scintillating fibers – capillary tubes structure was aluminized using PVD process to achieve optical isolation and good reflectivity for scintillation light in plastic to increase light collection efficiency
Construction of the Neutron Spectrometer with optically isolated $^6$Li glass fibers

Flat panel PMTs for measuring of scintillation separately in Plastic and in $^6$Li glass fibers

Plastic scintillator (PVT) surrounds aluminized structure of ceramic substrates with fibers

Matrix of capillary tubes with fibers (23 x 23) is held by 2 opaque ceramic substrates. Optical cement is used to glue fibers in place and to form optical pads for PMT attachment

Teflon-coated Silica glass capillary tubes (350um diameter), coated by additional layer of Aluminum. Each capillary tube holds 100 um thick $^6$Li glass fiber
Details of the Neutron Spectrometer Construction

After aluminization and SiO$_2$ application

Wrapped in Tyvek, ready for PMT

After casting in plastic scintillator
Neutron Spectrometer with attached PMTs

Fibers are viewed by PMTs at both ends. Completely Assembled Neutron Spectrometer
Typical PMT response on Neutron capture (red), at one side of Lithium glass fibers and corresponding signal, shaped by transconductance amplifier and active filter. Discrimination level was set at 50mV (1.5pe).
Neutron Capture Event

Outputs of two opposite sides of the Neutron channel on Neutron capture event (C1 and C2) and coincidence trigger output (C3)
A typical background gamma ray event: A secondary electron hits one (or several) fibers, causing coincident signal at both fiber ends (gold and pink traces) at a signal level of ~2 photoelectrons. The electron also creates a 21-photoelectron signal in the surrounding plastic scintillator (green trace), used as an anticoincidence rejection signal.
GEANT-4 simulation was performed for the manufactured prototype of the neutron spectrometer. Mean value of the photon flux in scintillating fibers due to neutron capture equals to 130 photons. Low output events (from 20 to 80 photons) are due to events occurred at the fiber wall when tritium nucleus escapes fiber and is absorbed by capillary tube.
Photon flux in scintillating fibers and plastic scintillator for gamma ray energies 200keV, 500keV, 1MeV and 2MeV. Most gamma ray events creates less that 5 photons in $^6\text{Li}$ scintillating glass fibers due to small diameter (100µm).
Photon flux in scintillating fibers and plastic scintillator for two gamma ray energies 200keV and 1 MeV. Major amount of gamma ray events are rejected due to low photon flux in glass fibers 100$\mu$m in diameter. Gammas that produce enough light in fibers to generate neutron channel coincidence signal also create significant photon flux in plastic and therefore are rejected by plastic channel anticoincidence signal.
Tests with Americium-Beryllium Neutron Source

One neutron channel amplitude spectrum (red) and associated neutron energy (preceding plastic scintillation due to recoil proton) (green), acquired using AmBe neutron source, which provides Neutrons of the from 4 to 8 MeV. Histogram on the left shows neutron capture events collected without moderator and contains more energetic neutrons. Right histogram shows moderated lower energy neutron spectrum, collected using 4-inch surrounding polyethylene.
Aluminum target is installed on the Proton beam line to stop 100MeV protons. Detector is connected to ANS data acquisition system and located at 30deg. angle off beam line. Performance of detector is tested in complex radiation environment, which contains intense neutron and gamma radiation.
Neutron Capture Spectrum Collected at IUCF

One of two neutron channel amplitude spectrum (red) and associated neutron energy (green), collected with data acquisition system at the Indiana University Cyclotron using 100MeV proton beam at the 1inch-thick aluminum target.
Neutron Channel PMT Outputs

Neutron capture responses of two PMTs, acquiring scintillation light at both fiber ends. One side has consistently lower output due to manufacturing defect, that causes light loses at one detector side. Neutron capture thresholds were set at 2.5 p.e. for the detector side 1 and at 1.5 p.e. - for the detector side 2.
Light Collection Efficiency from Plastic Scintillator

Light collection efficiency characteristics, taken by aiming of the proton beam at different areas of the detector, starting from the detector top, where the plastic PMT is attached. Aluminum coating caused significant light absorption for events that occur far from PMT behind aluminized fibers.

Reflectivity characteristics for aluminum and silver coatings versus scintillation light wavelength. To improve light collection efficiency green-emitting scintillating casting resin BC-490G and silver coating were chosen for the next detector prototype.
Summary of Results

• The capture-gated coincidence method has been demonstrated.
• The neutron capture signal can be optically isolated from the plastic scintillator, permitting the plastic scintillator to be used as an anti-coincidence detector to reject events associated with external charged particles and gammas.
• Additional gamma ray rejection factor can be achieved by using the anti-coincidence function of the plastic scintillator if $^6\text{Li}$ scintillating glass fibers have more than 35 $\mu$m absorption coating to stop escaping tritium nucleus from neutron capture reaction.
The End