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[1,2]*. It has been shown that secondary neutrons can account for up to 50% if the total dose-equivalent received by the crew*[3] *.*

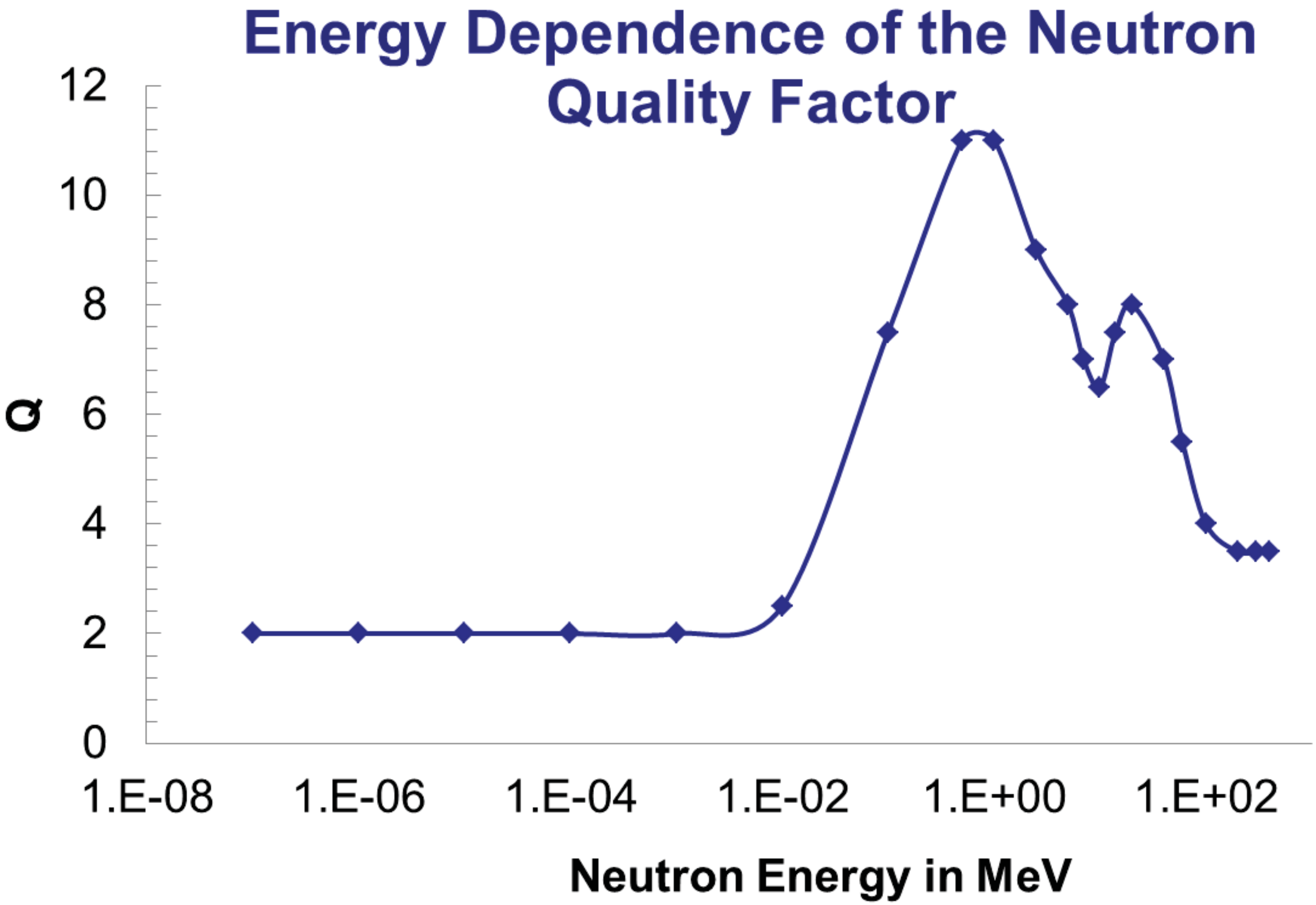
Technical Approach: Use isolated fast and thermal neutron detectors.

Unfold the neutron energy spectrum from the signal recorded in a plastic scintillator. Identify the neutrons using signals from ^{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.*

[1] "Radiation protection for human missions to the Moon and Mars", L. C. Simonsen and J. E. Nealy, NASA Tech. Paper no. TP-3079 (1991).

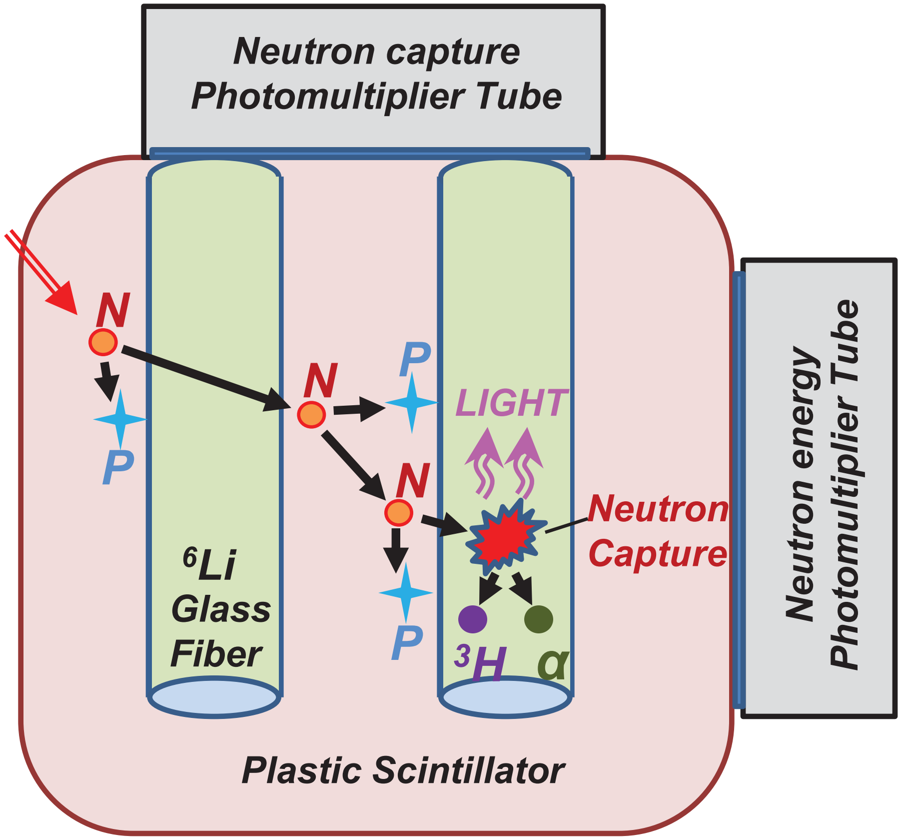
[2] "The Ionizing Radiation Environment on the Moon", J. H. Adams, M. Bhattacharya, Z. W. Lin ,G. Pendleton and J. W. Watts, Adv. in Space Research, **40**, p. 338–341 (2007).

[3] "Modeling of Secondary Neutron Production From Space Radiation Interactions", IEEE Trans. on Nucl. Sci., 49, 2800-2804 (2002).

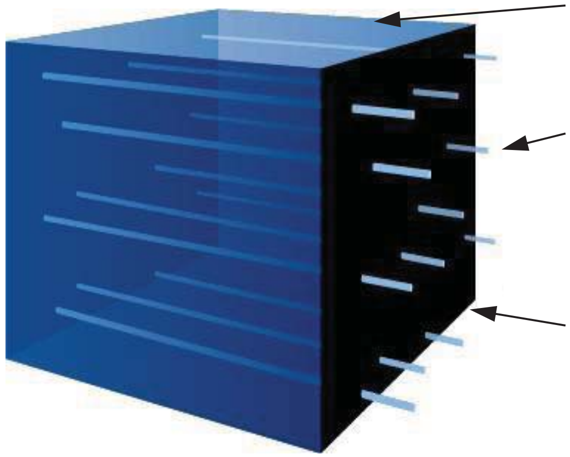


The data are taken from“20.1004 Units of radiation dose”, U.S. Nuclear Regulatory Commission, http://www.nrc.gov/reading-rm/doc-collections/cfr/part020/part020-1004.html

Neutron Spectrometer Concept



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.



Plastic Scintillator

Encapsulated Optically Isolated Scintillating Glass Fibers

Opaque ceramic Substrate

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}Be(n,α)^{7}Li + γ and ^{10}Be(n,α)^{7}Li deposits either 2.79 or 2.31 MeV (if γ escapes)
- **Li(n, α)^{3}H deposits 4.78 MeV; preferred because the large unique capture signal**

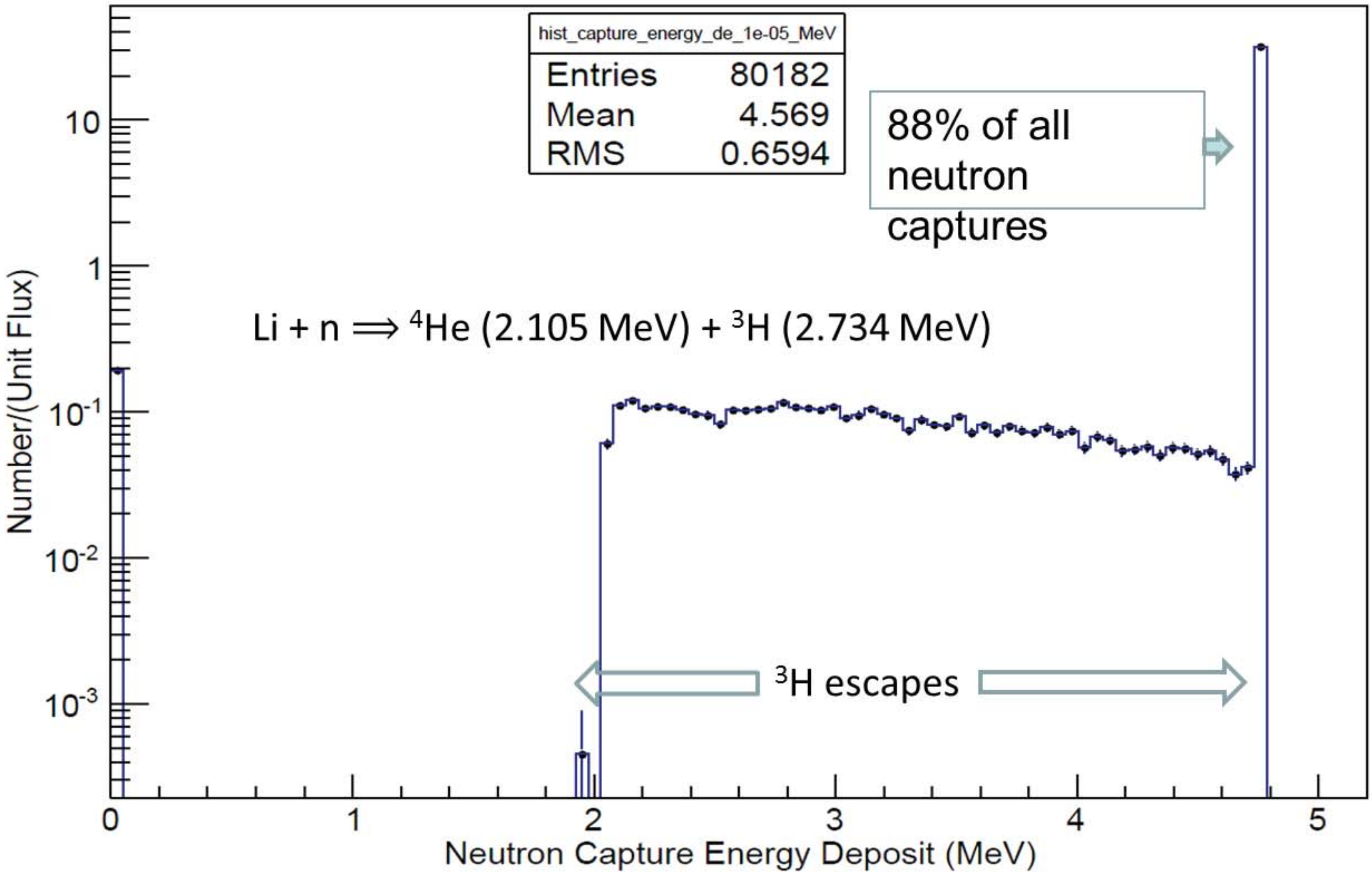
The choices for fiber cladding/encapsulation are:

- 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 + α and ^{3}H are contained**

Choice of Fibers:

- **Simulations have shown that 100-150 μm diameter fibers are the best tradeoff between containing the α , ^{3}H and creating scintillation associated with γ rays not large enough to mimic neutron captures**

Thermal Neutron Capture Signal in the ^{6}Li-loaded Scintillating Glass Fibers

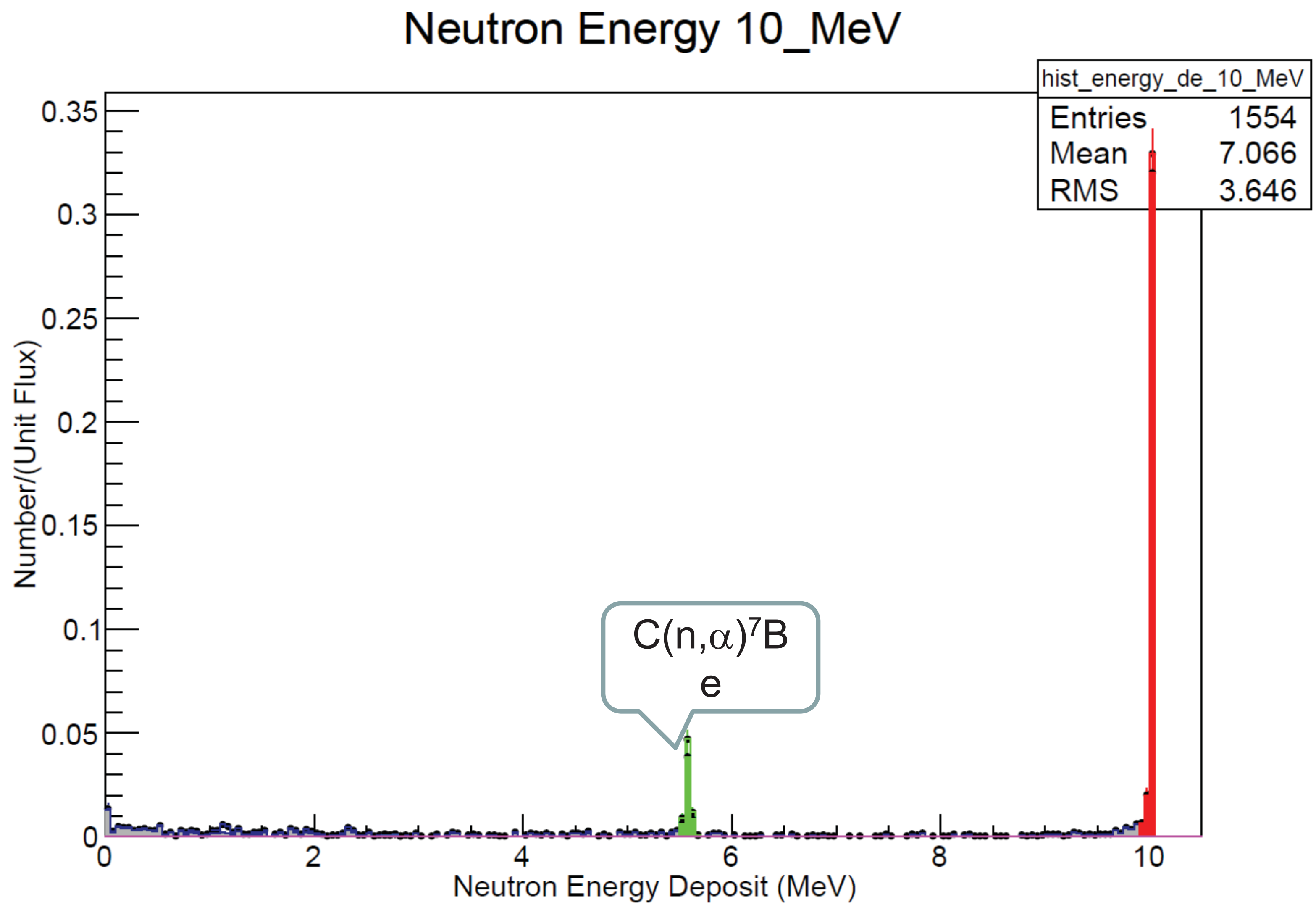


88% of all neutron captures

Li + n $\Longrightarrow$ ^{4}He (2.105 MeV) + ^{3}H (2.734 MeV)

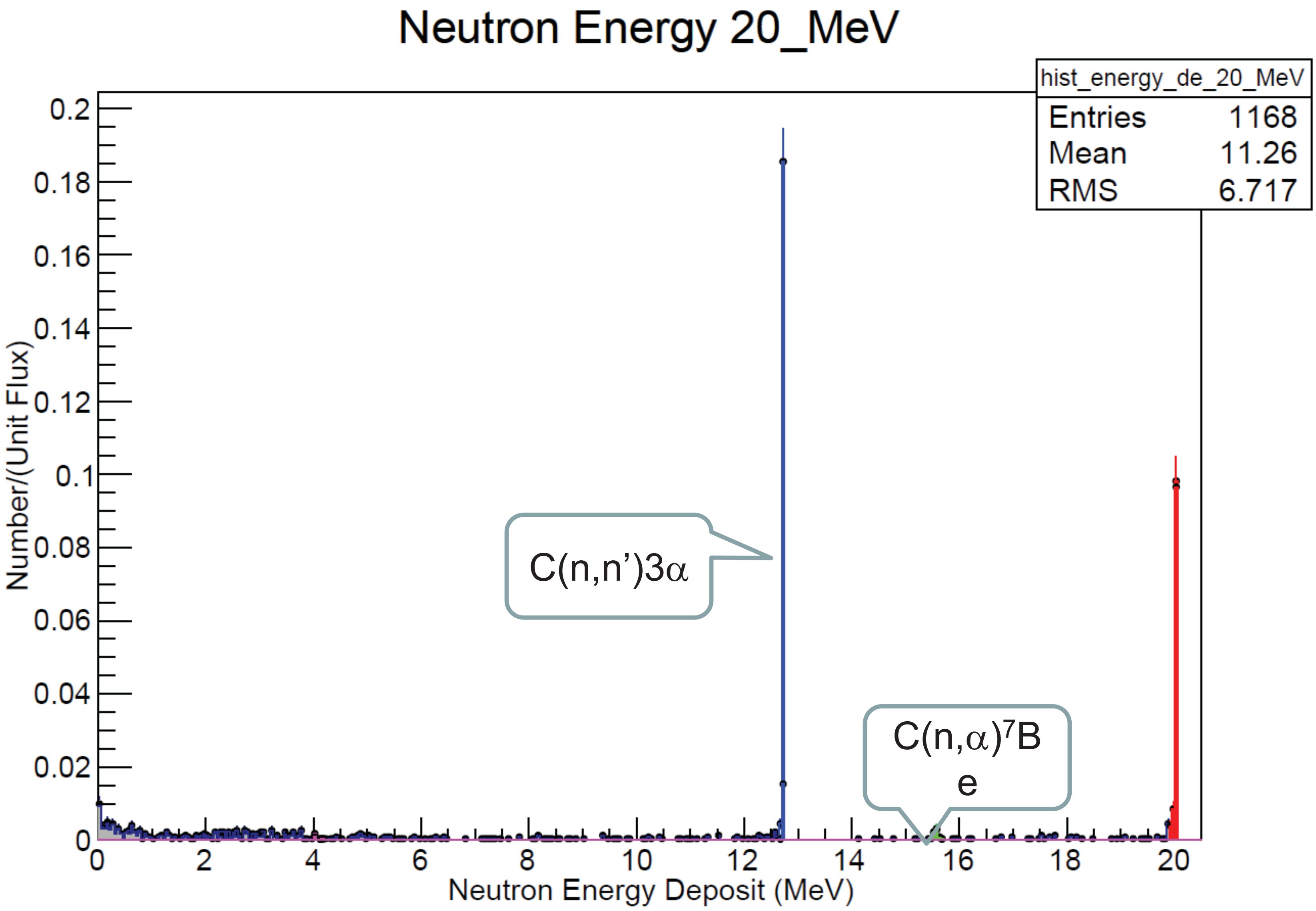
^{3}H escapes

Pre-Capture Signal in the Plastic Scintillator 10 MeV



C(n,α)⁷Be

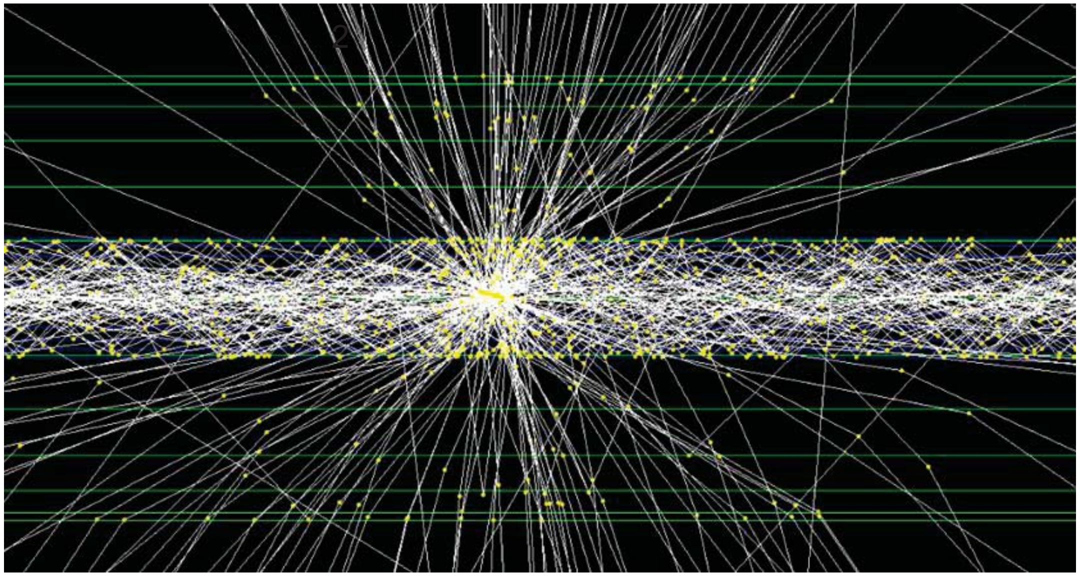
Pre-Capture Signal in the Plastic Scintillator 20 MeV



Using the Fiber as an Optical Wave Guide

<u>Critical angle for total internal reflection</u>

- $sin^{-1}(1.31/1.5258) = 30.8°$
- 25.3 go to each phototube
- Each tube produces 6.3 photoelectrons
- Threshold = 2 p.e.s or 0.9 MeV
- Estimated efficiency of γ's to mimic thermal neutron capture signals: ~10^{-6}.



Fibers Inserted in Capillary Tubes

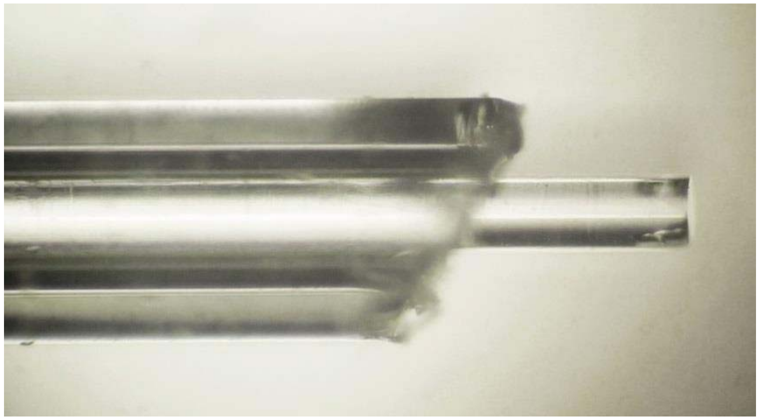
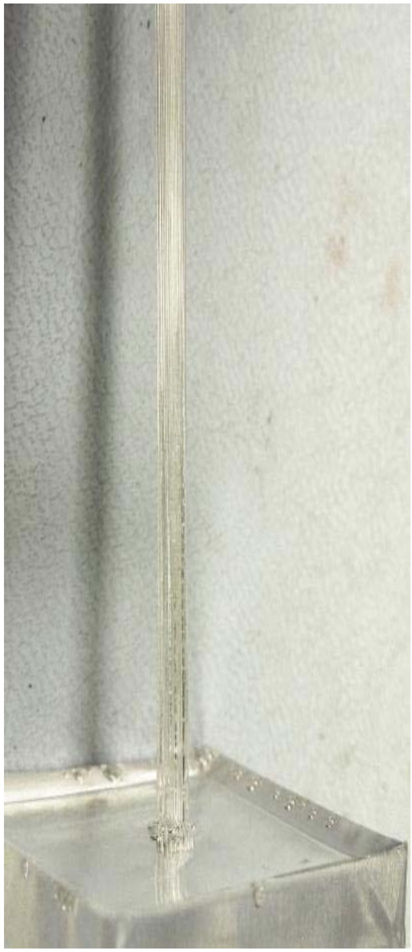


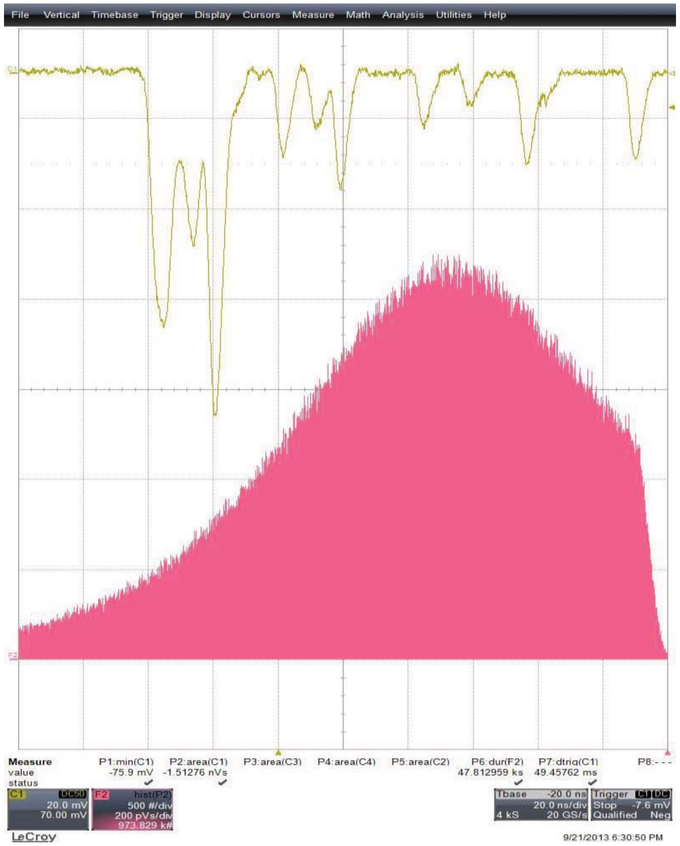
Image of Teflon coated fused silica capillary tube (OD=363um; ID=150um) with inserted ^{6}Li glass fiber (OD = 100um)

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



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value      -75.9 mV   -1.51276 nVs                                          47.812959 ks  49.45762 ms
status         ✓            ✓                                                     ✓             ✓
C1 DC50  20.0 mV  70.00 mV
F2 hist(P2)  500 #/div  200 pVs/div  973.829 k#
Tbase -20.0 ns  20.0 ns/div  4 kS  20 GS/s
Trigger C1 DC  Stop -7.6 mV  Qualified Neg
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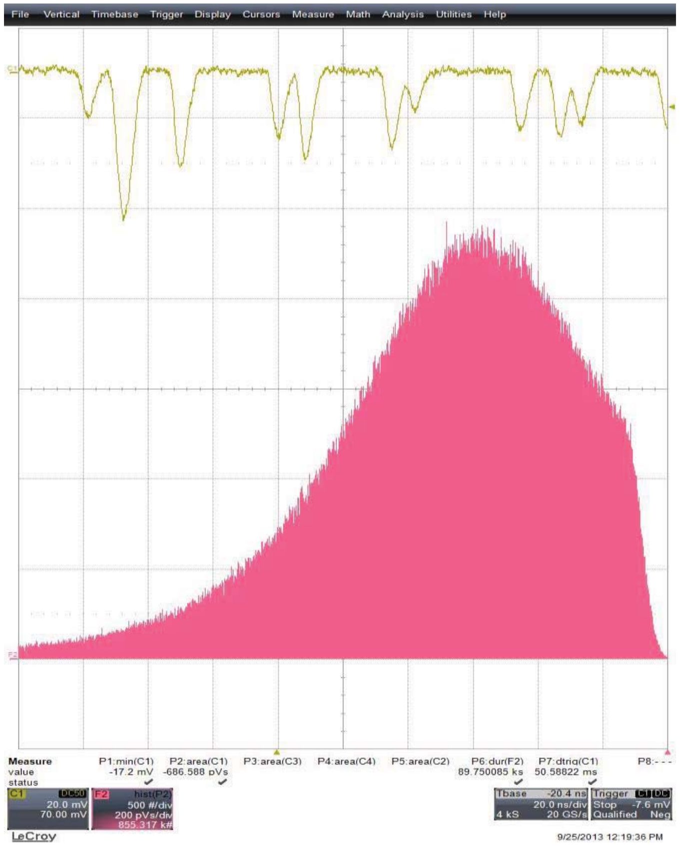
Am-241 spectrum. Test article consists of Teflon-coated fused silica capillary tubes with inserted ^{6}Li glass fibers held in air . Alpha source was attached at the opposite to PMT end of fibers. PMT response was integrated over 160ns. Scale: 200pV*s/div (max =~ 14pe)



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Measure   P1:min(C1)  P2:area(C1)    P3:area(C3)  P4:area(C4)  P5:area(C2)  P6:dur(F2)    P7:dtrig(C1)  P8:- - -
value      -17.2 mV   -686.588 pVs                                          89.750085 ks  50.58822 ms
status         ✓            ✓                                                     ✓             ✓
C1 DC50  20.0 mV  70.00 mV
F2 hist(P2)  500 #/div  200 pVs/div  855.317 k#
Tbase -20.4 ns  20.0 ns/div  4 kS  20 GS/s
Trigger C1 DC  Stop -7.6 mV  Qualified Neg
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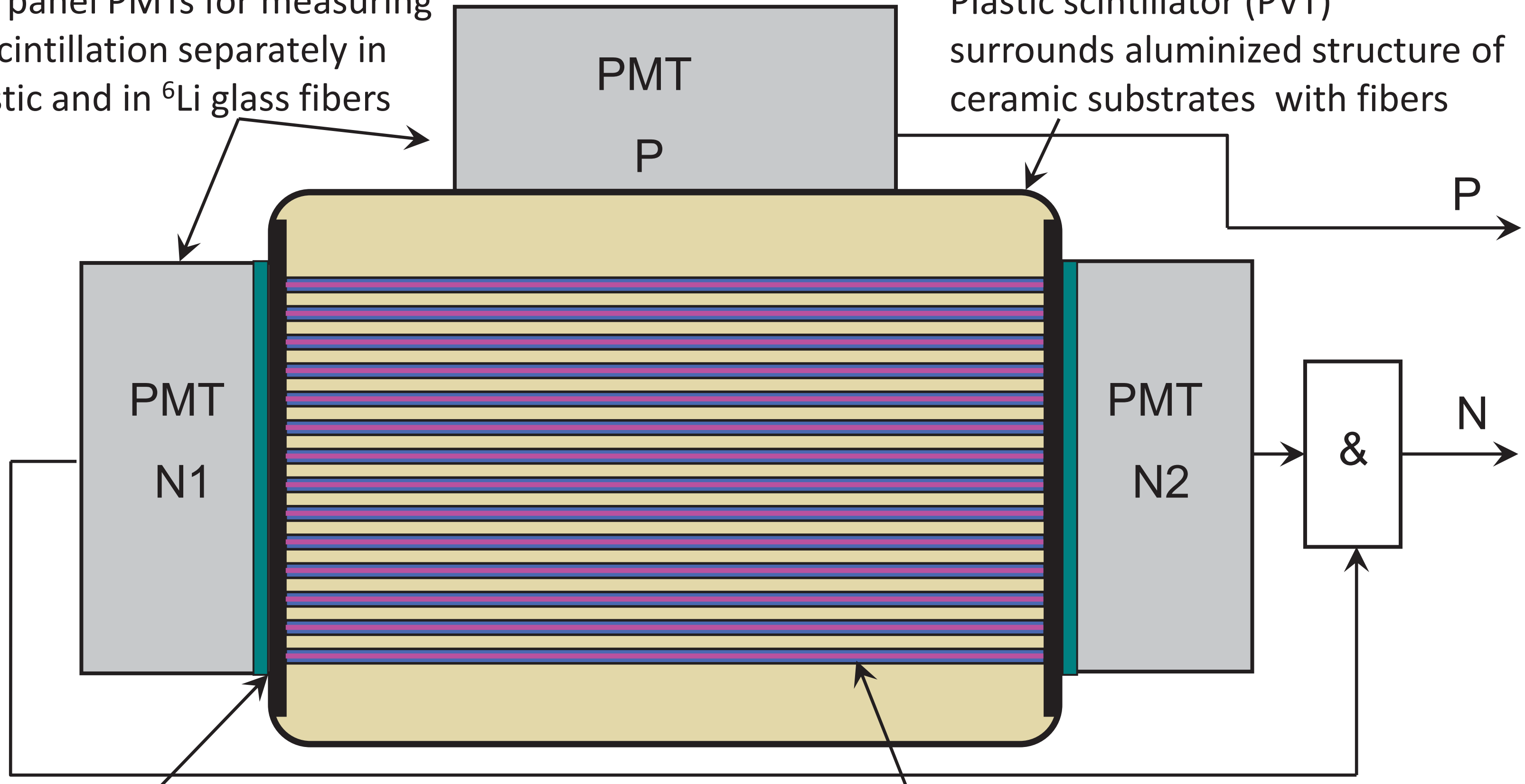
Am-241 spectrum. Teflon-coated capillary tubes with inserted ^{6}Li glass fibers are submerged in BC600 over 3.0” . Same measurement conditions. 200pV*s/div (max =~ 12pe)

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

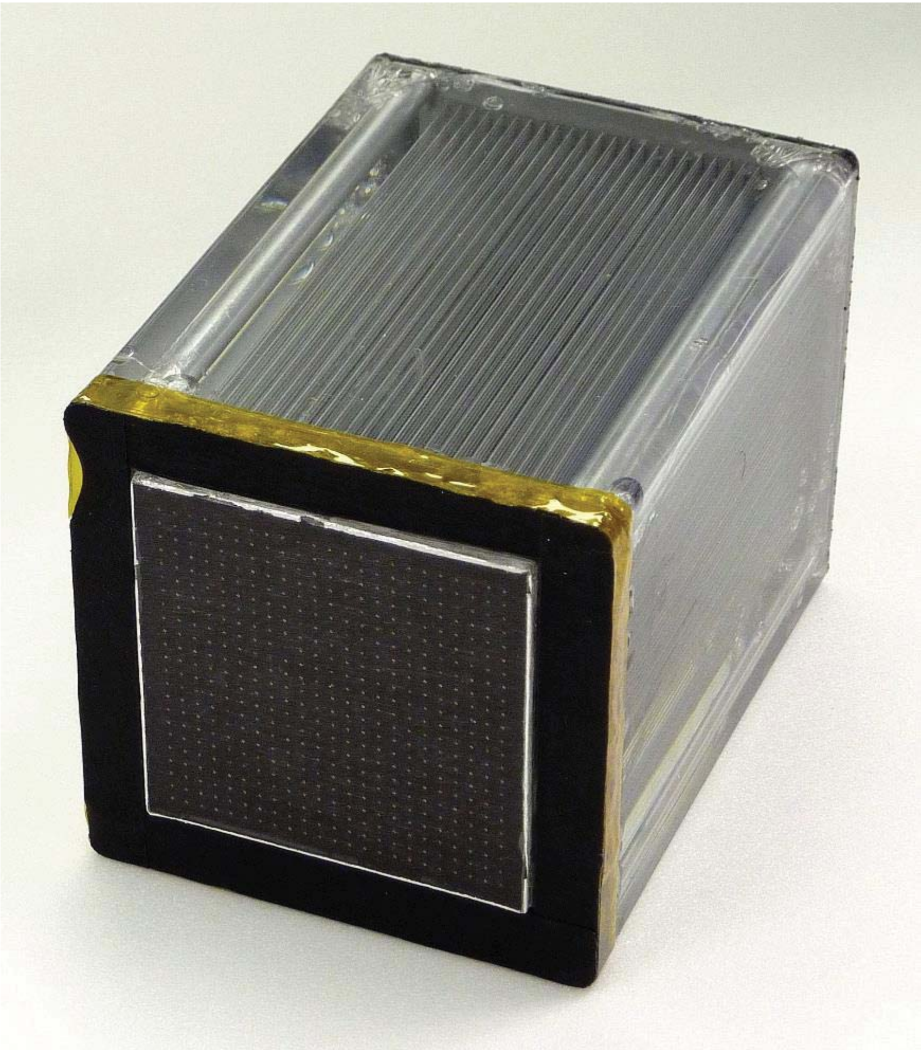
Plastic scintillator (PVT) surrounds aluminized structure of ceramic substrates with fibers

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

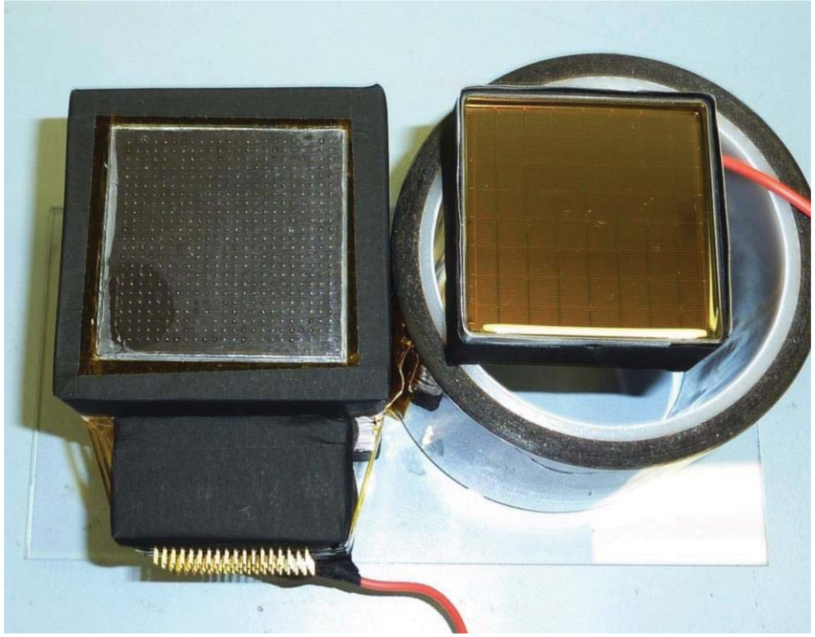
After aluminization and SiO_2 application



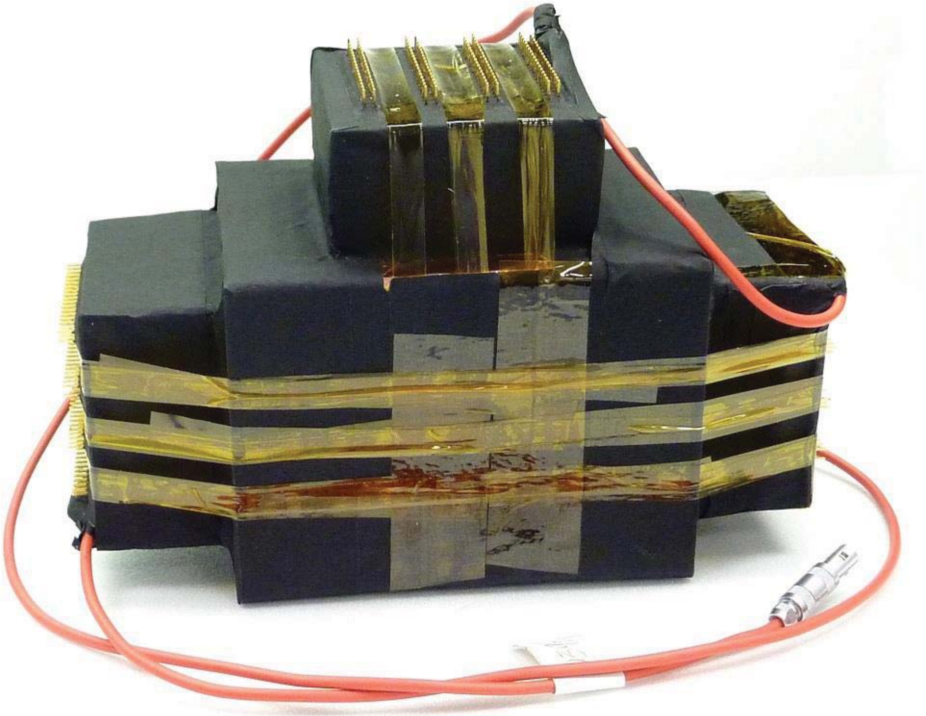
After casting in plastic scintillator

Wrapped in Tyvek, ready for PMT

Neutron Spectrometer with attached PMTs

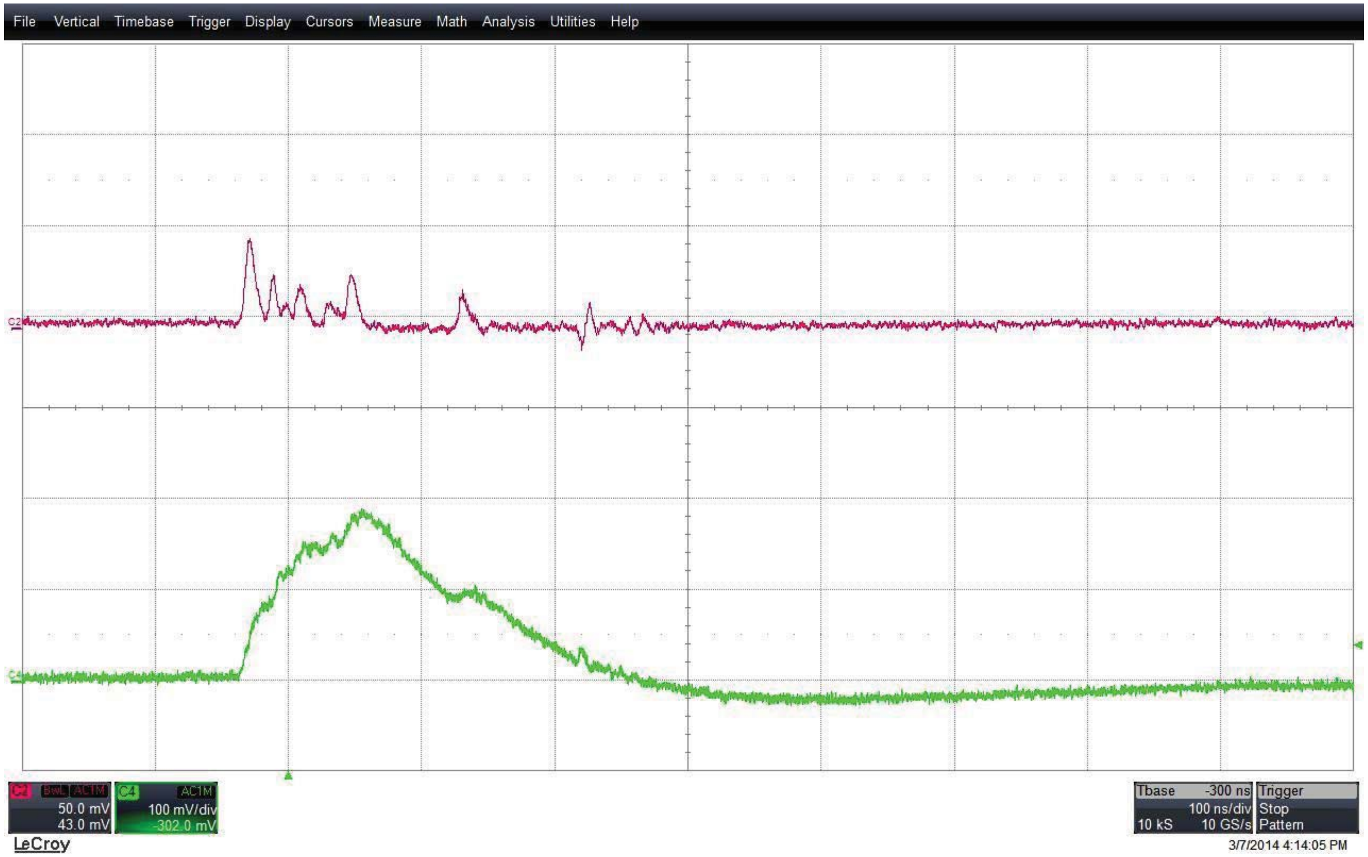


Fibers are viewed by PMTs at both ends.



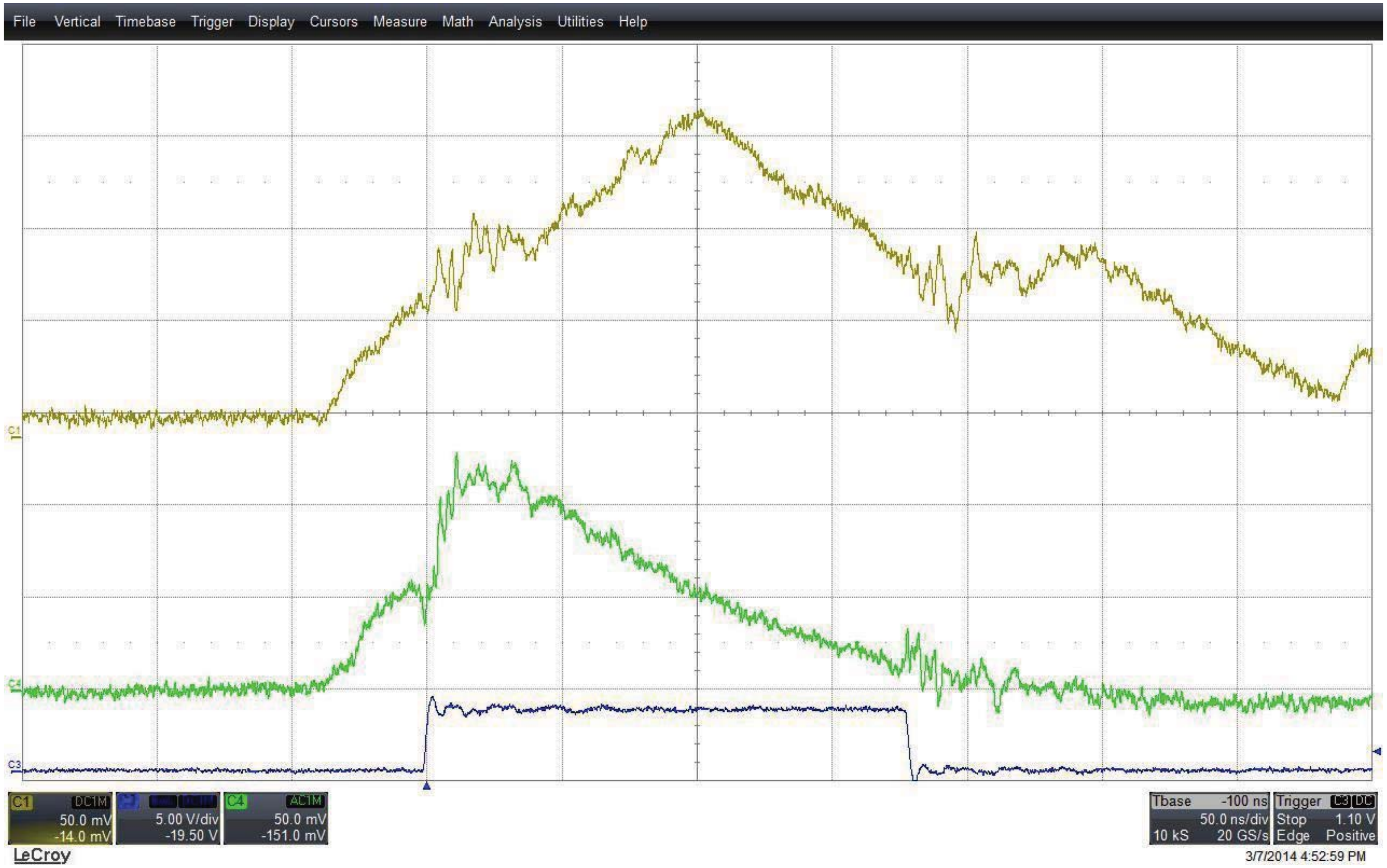
Completely Assembled Neutron Spectrometer

Neutron Channel Signal Conditioning



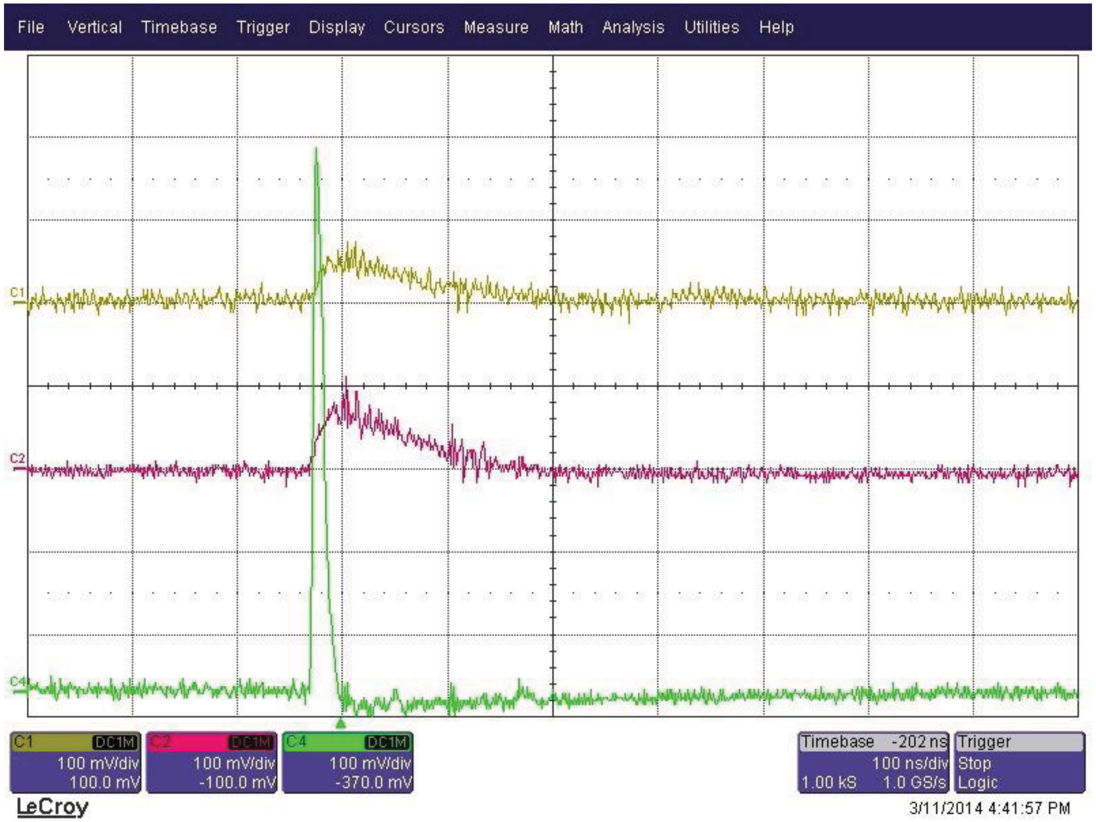
Typical PMT response on Neutron capture (red), at one side of Lithium glass fibers and corresponding signal , shaped by transconductance amplifier and active filter. Discrimination level was set at 50mV (1.5pe).

Neutron Capture Event



Outputs of two opposite sides of the Neutron channel on Neutron capture event (C1 and C2) and coincidence trigger output (C3)

Gamma Ray Event



C1 DC1M 100 mV/div 100.0 mV

C2 DC1M 100 mV/div -100.0 mV

C4 DC1M 100 mV/div -370.0 mV

Timebase -202 ns 100 ns/div 1.00 kS 1.0 GS/s

Trigger Stop Logic

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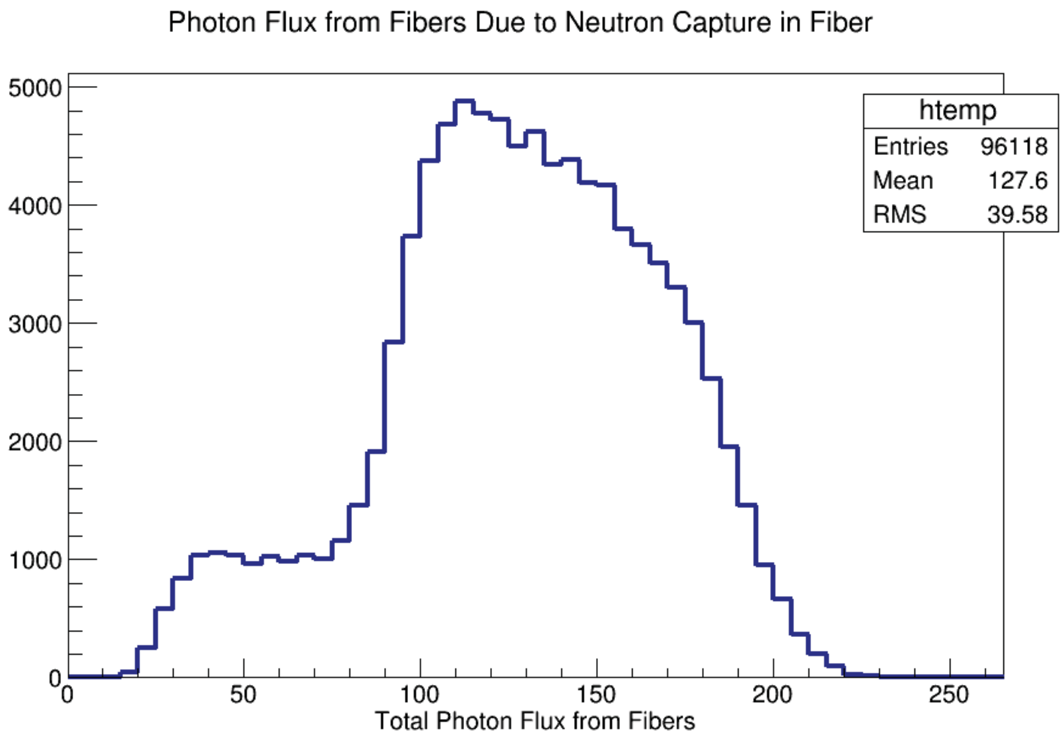
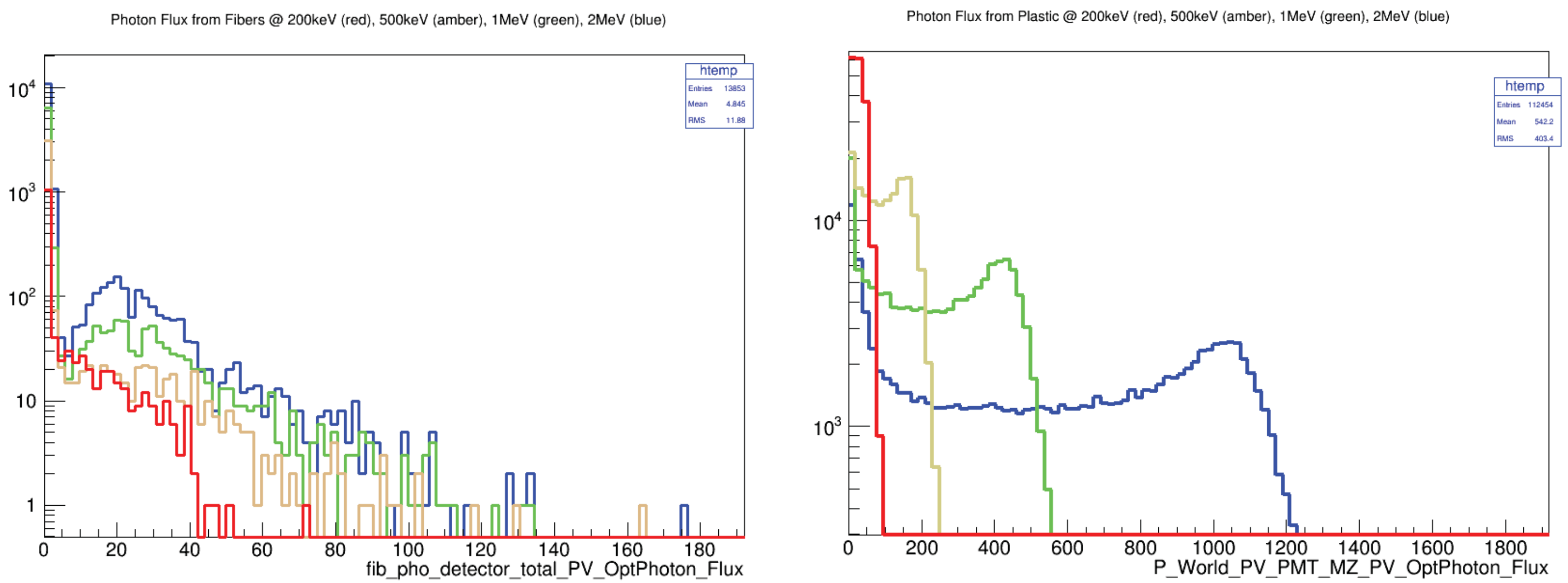
A typical background gamma ray event: A secondary electron hits one (or several) fibers, causing coincident signal at both fiber ends (gold and pink traces) at a signal level of ~2 photoelectrons. The electron also creates a 21-photoelectron signal in the surrounding plastic scintillator (green trace), used as an anticoincidence rejection signal

GEANT-4 simulation of N-capture events in fibers



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.

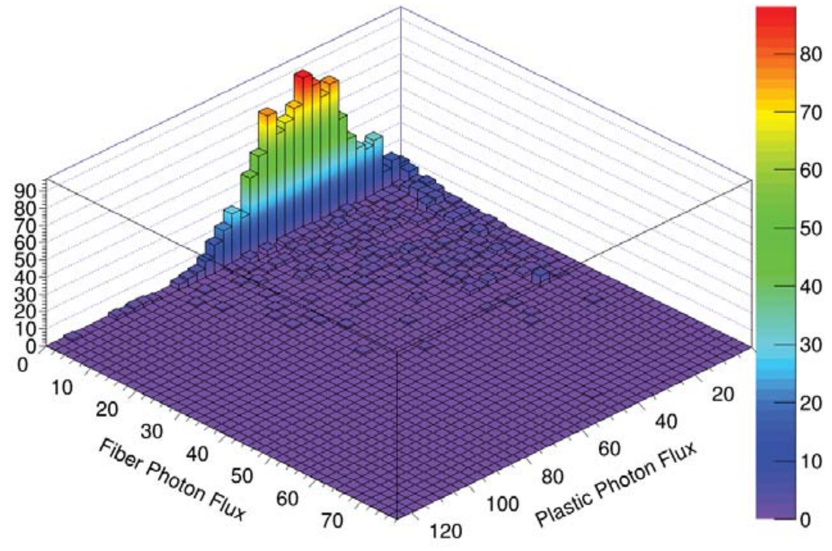
GEANT4 Simulation. Gamma rays



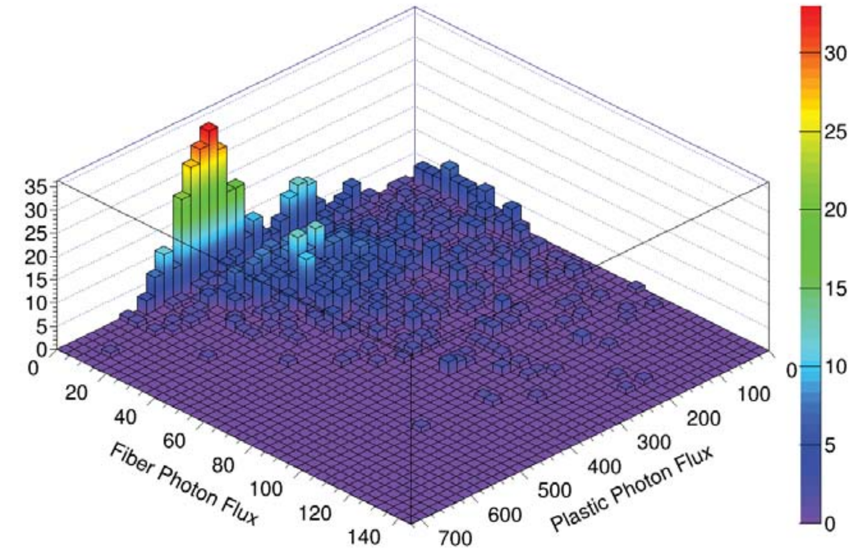
Photon flux in scintillating fibers and plastic scintillator for gamma ray energies 200keV, 500kV, 1MeV and 2MeV. Most gamma ray events creates less that 5 photons in ^{6}Li scintillating glass fibers due to small diameter (100μm).

GEANT4 Simulation. Gamma rays (continued)

gamma @ 200keV Fiber vs Plastic Flux (both > 0) 1356 events/~330,000

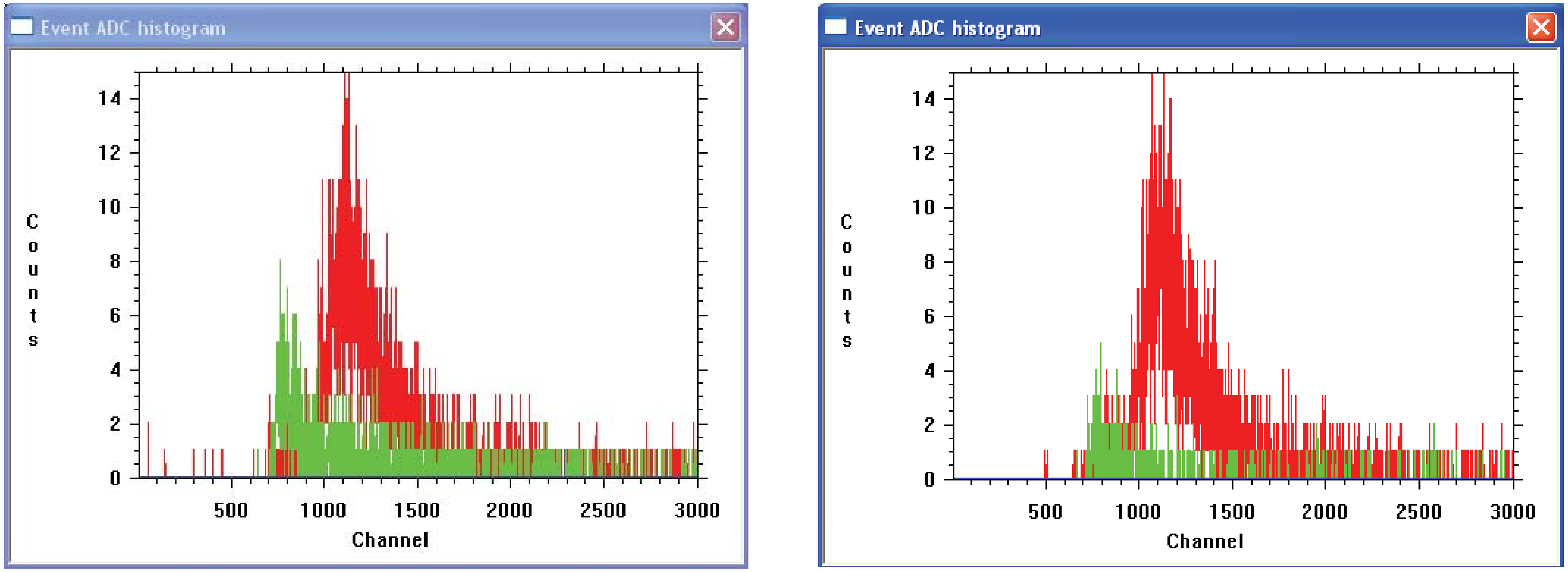


gamma @ 1MeV, Fiber vs Plastic Flux (both > 1), 1209 events/~330,000



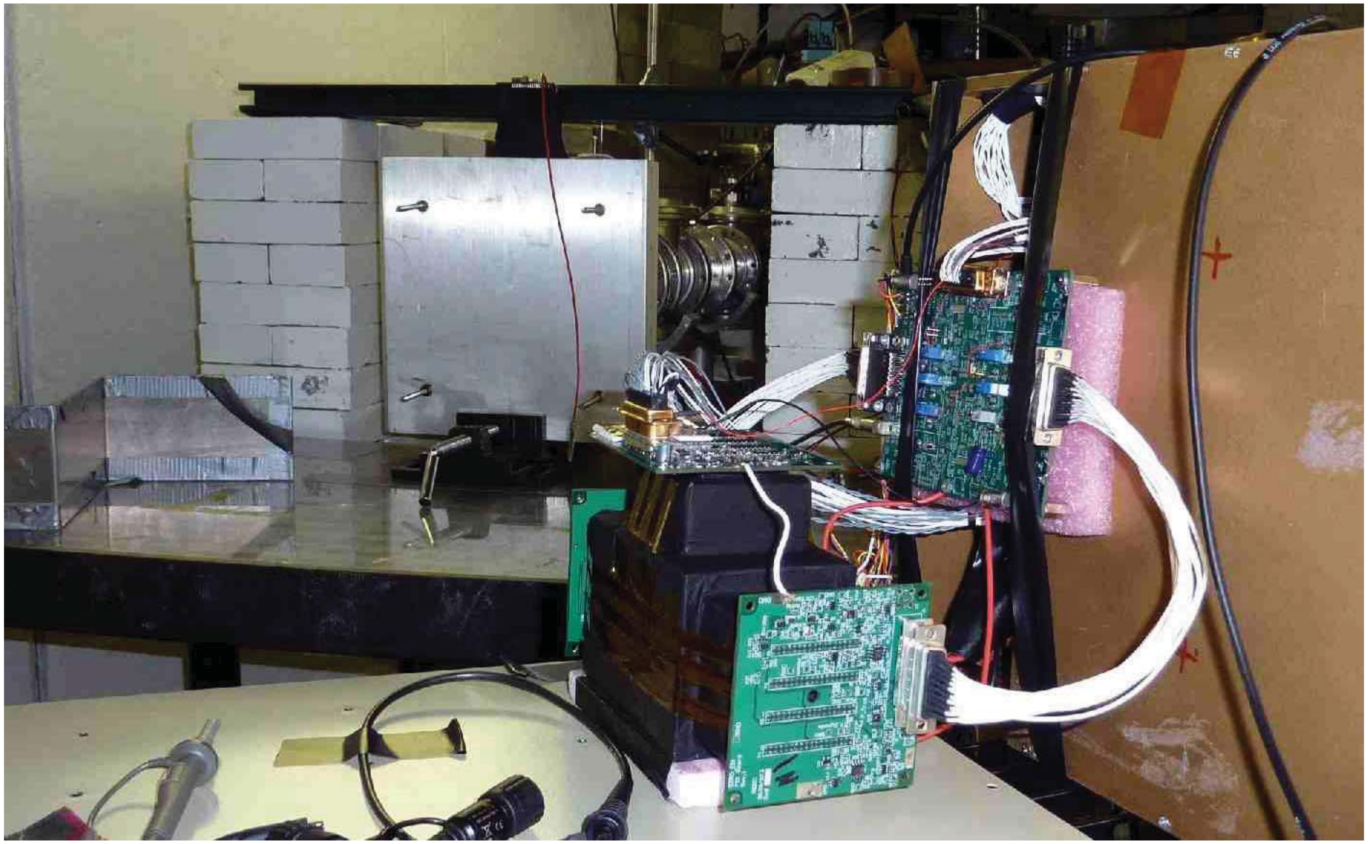
Photon flux in scintillating fibers and plastic scintillator for two gamma ray energies 200keV and 1 MeV. Major amount of gamma ray events are rejected due to low photon flux in glass fibers 100μm in diameter. Gammas that produce enough light in fibers to generate neutron channel coincidence signal also create significant photon flux in plastic and therefore are rejected by plastic channel anticoincidence signal.

Tests with Americium-Beryllium Neutron Source



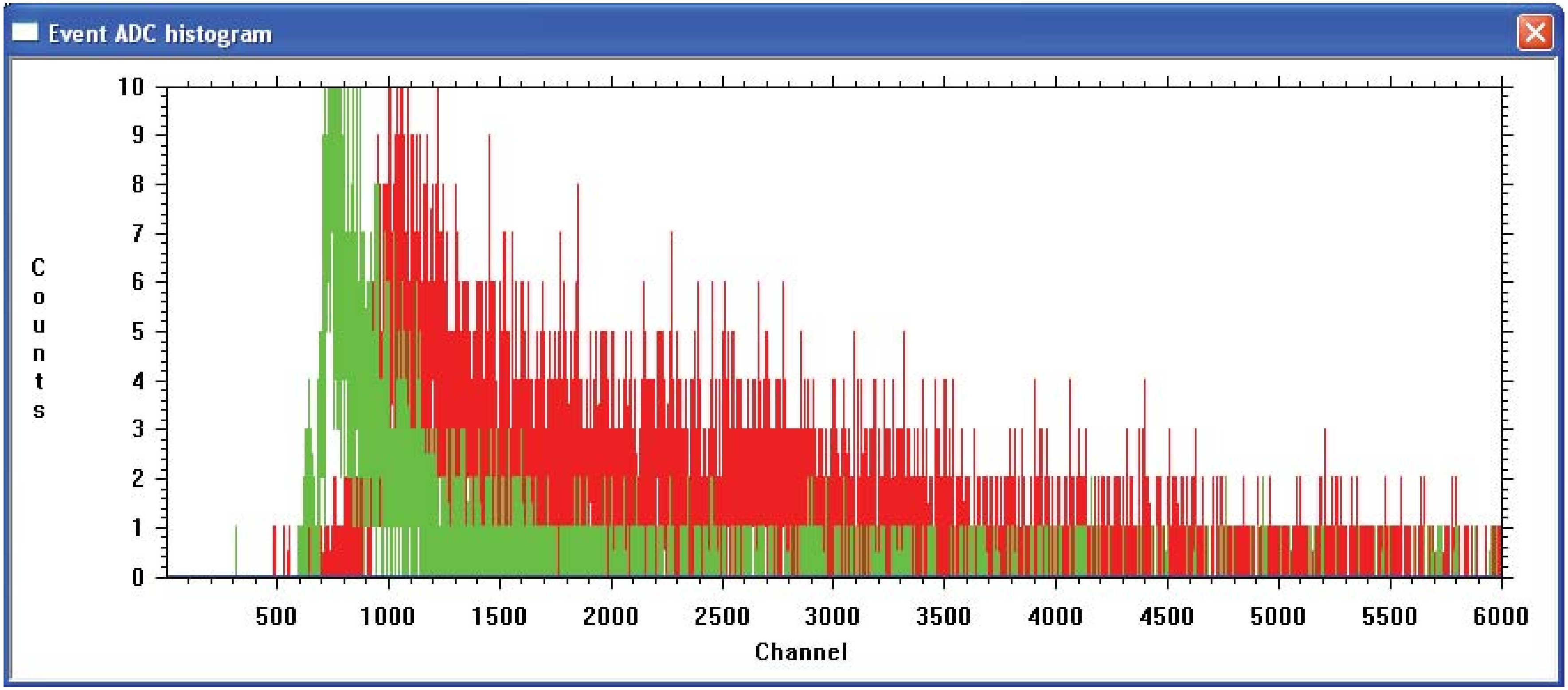
One neutron channel amplitude spectrum (red) and associated neutron energy (preceding plastic scintillation due to recoil proton) (green), acquired using AmBe neutron source, which provides Neutrons of the from 4 to 8 MeV. Histogram on the left shows neutron capture events collected without moderator and contains more energetic neutrons. Right histogram shows moderated lower energy neutron spectrum, collected using 4-inch surrounding polyethylene.

Test Setup at IU Cyclotron



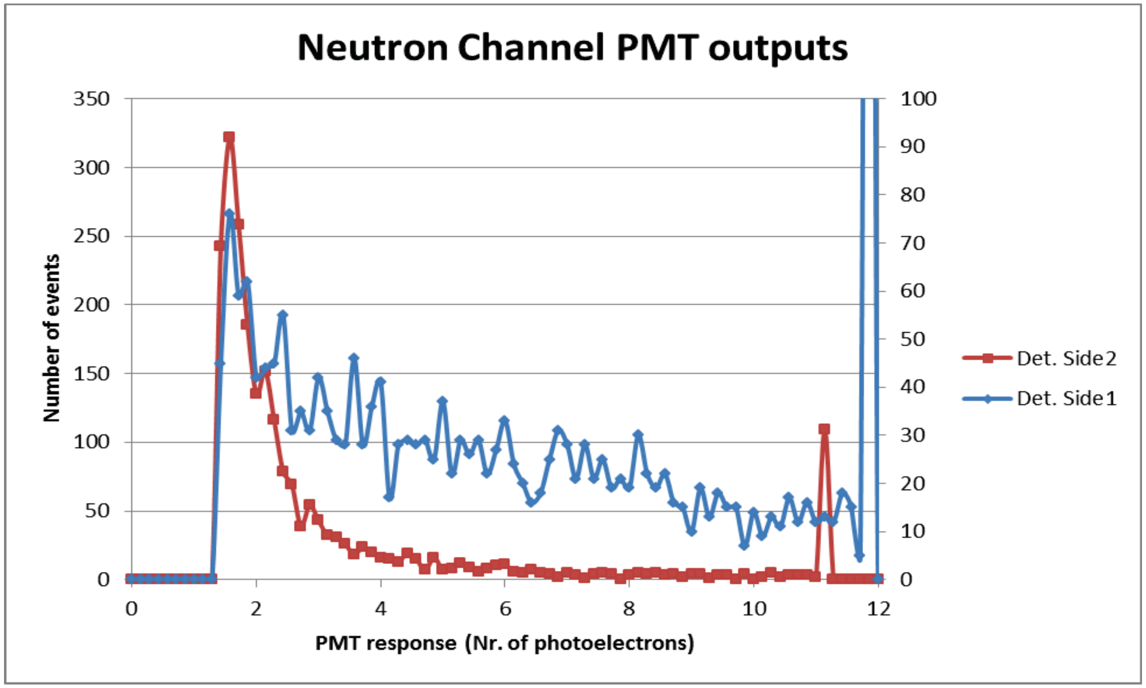
Aluminum target is installed on the Proton beam line to stop 100MeV protons. Detector is connected to ANS data acquisition system and located at 30deg. angle off beam line. Performance of detector is tested in complex radiation environment, which contains intense neutron and gamma radiation.

Neutron Capture Spectrum Collected at IUCF



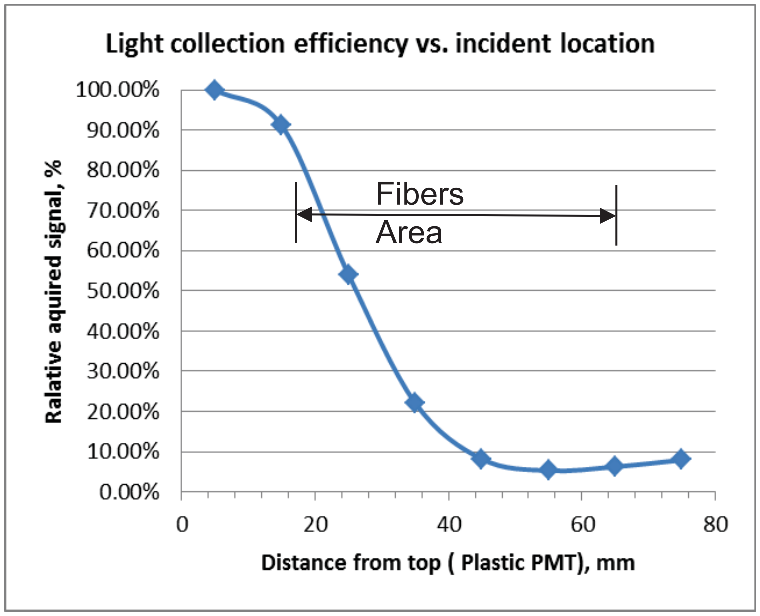
One of two neutron channel amplitude spectrum (red) and associated neutron energy (green), collected with data acquisition system at the Indiana University Cyclotron using 100MeV proton beam at the 1inch-thick aluminum target.

Neutron Channel PMT Outputs

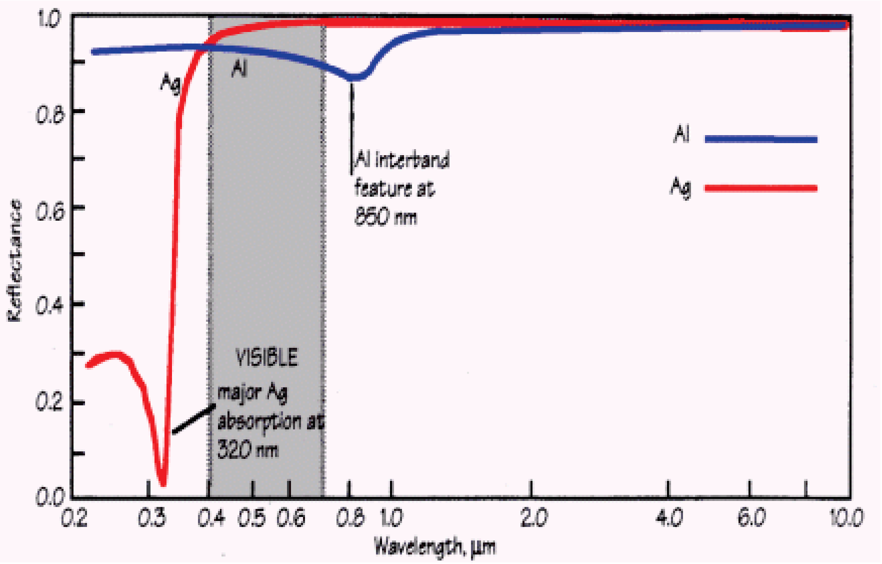


Neutron capture responses of two PMTs, acquiring scintillation light at both fiber ends. One side has consistently lower output due to manufacturing defect, that causes light loses at one detector side. Neutron capture thresholds were set at 2.5p.e. for the detector side 1 and at 1.5 p.e. - for the detector 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 event associated with external charged particles and gammas
- Additional gamma ray rejection factor can be achieved by using anti-coincidence function of the plastic scintillator if ^{6}Li scintillating glass fibers have more that 35μm absorption coating to stop escaping tritium nucleus from neutron capture reaction

The End