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Optimization of a Fast Neutron Scintillator for Real-Time Pulse Shape Discrimination in the Transient Reactor Test Facility (TREAT) Hodoscope

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***Abstract*–We present a multi-channel, fast-neutron/photon detection system that uses ZnS(Ag) scintillator detectors. The system employs field-programmable gate arrays to pulse-shape analysis for real-time all-digital neutron/photon differentiation, producing particle-dependent pulse height and temporal distributions while allowing count rates in excess of 1,000,000 events per second per channel. The system size is scalable in blocks of 16 channels.**

I. Background

Idaho National Laboratory (INL) is currently leading activities for the refurbishment and restart of the Transient Reactor Test Facility (TREAT) located at INL. Prior to this, the reactor was in standby status for 22 years. One of the main test instruments at the TREAT facility is the Fuel Motion Monitoring System (FMMS), capable of measuring the motion of fissionable material in test fuel as the fuel fails under simulated accident-like conditions. This instrument, historically know as a hodoscope, is equipped with 360 fast-neutron detectors made from silver-activated zinc sulfide (ZnS(Ag)) scintillator material. These detectors are in a collimated matrix located just outside of the reactor with an unobstructed view of the experimental test location at the reactor's center. Unfortunately, these detectors along with the data acquisition system became antiquated and are no longer usable in their current state. Efforts to refurbish the detectors are currently underway and a state-of-the-art data acquisition system is now under development. The work presented here focuses on the issues associated with real-time photon-neutron discrimination and data processing of the 360-channel FMMS.

II. Detector and Response

ZnS(Ag) has been used as a fast neutron detector for over 60 years and is still commercially available.[1] The original FMMS detectors were fabricated by dispersing ZnS(Ag) crystals in acrylic to form a small wafer. These wafers were then coupled to two half cylinders of acrylic to provide a light guide on each side of the wafer. The assembled "buttons" were coupled to photomultipliers to capture the scintillation created from charged particle interactions in the wafer. A full detector assembly coupled to a photomultiplier tube, along with a ZnS(Ag) wafer decoupled from the acrylic waveguides, is shown in Fig. 1.

Fig. 1. A complete ZnS(Ag) detector assembly and a ZnS(Ag) wafer decoupled from the waveguides.

ZnS(Ag) produces scintillation when excited by charged particle interactions. The amount of light and its timing structure is dependent upon the type of charged-particle interacting in the material.[2] This allows for the discrimination between proton recoils originating from neutron interactions and electron recoils originating from photon interactions based on the shape of the resulting pulse of scintillation. Shown in Fig. 2 are 1000 pulse averages of both neutron (blue) and photon (red) responses from ZnS(AG). The neutron curve has a longed-lived delayed component to its response that lasts for well over a microsecond, while the photon response has a rapid die-away on the order of 100 nanoseconds.

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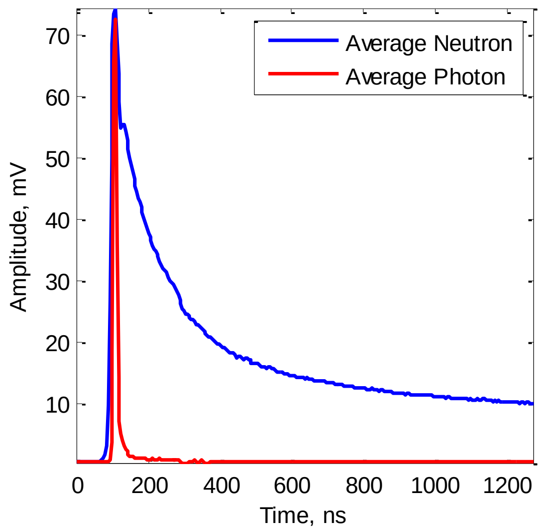

Fig. 2. The average pulse shapes of neutrons and photons in a ZnS(Ag). Neutron pulses have a long-lived light component compared to photon pulses.

When developing an effective means of pulse shape discrimination (PSD) a multi-pulse averaged shape can be misleading. Examples of single photon and neutron responses are shown in Fig. 3. These plots demonstrate how the neutron response is actually composed of multiple fast light emissions that vary significantly from pulse to pulse. Hence, while the fast signal from a photon could easily be discriminated with a simple low pass filter, the use of such a filter would misclassify a large fraction of the neutron pulses and effectively reduce neutron detection efficiency.

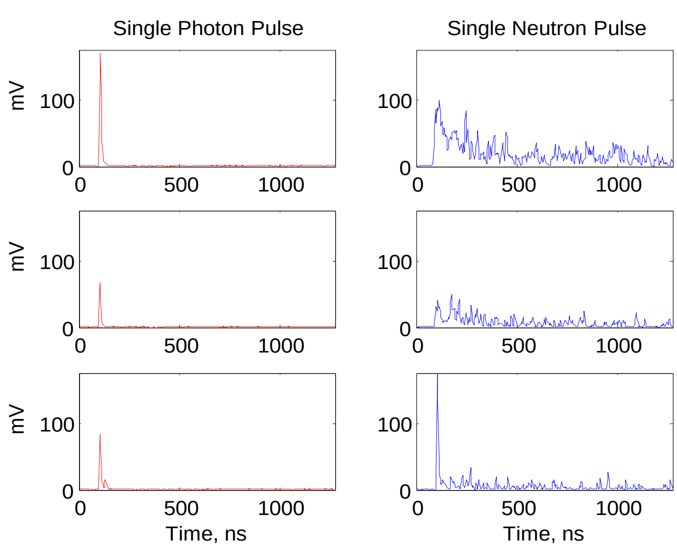

Fig. 3. Examples of digitized single photon and neutron pulses. Neutron interactions (BLUE) produce light in a stochastic nature for an extended period of time beyond that of a photon induced pulse (RED).

Traditional use of these detectors in the TREAT hodoscope system did not employ digital waveform processing. Pulse current was simply integrated and a total charge threshold was applied to discriminate between photon and neutron responses. Through implementation of state-of-the-art digitization technology the refurbished hodoscope scintillator array now has the ability to not only discriminate but differentiate neutron and photon events and to perform at levels of detection efficiency and timing resolution that was not historically achievable. However, an efficient and robust method to digitally classify neutron and photons was needed to make full use of this technology.

III. Pulse Shape Discrimination Methods

A method for PSD was developed and optimized that provides a means of differentiating incident neutrons from photons instead of simply rejecting photon events. Time and amplitude information were also persevered to offer additional PSD algorithm parameters if needed. The developed algorithm is a charge integration technique, using a two-dimensional look up table (LUT) rather than simple threshold discrimination. This allows complex neutron and photon regions to be defined in PSD parameter space. The method was implemented in a Struck digitizer (Model SIS3316, 16-channel, 14-bit, 250 MS/s) which allows for channel-specific LUT definitions designed for operational conditions where PSD mapping is not identical from detector to detector.

Pulses are digitized over a 2-microsecond window. There is a 760-nanosecond-wide region prior to the peak which is used to determine the average baseline voltage. The digitized pulse is divided into two regions for charge integration: an 80-nanosecond region that captures the peak of the pulse followed immediately by a 760-nanosecond-wide tail region. The PSD value is calculated by taking the baseline subtracted ratio of the peak region to the tail region. A schematic demonstrating the baseline, peak, and tail-integration regions for a digitized pulse is shown in Fig. 4.

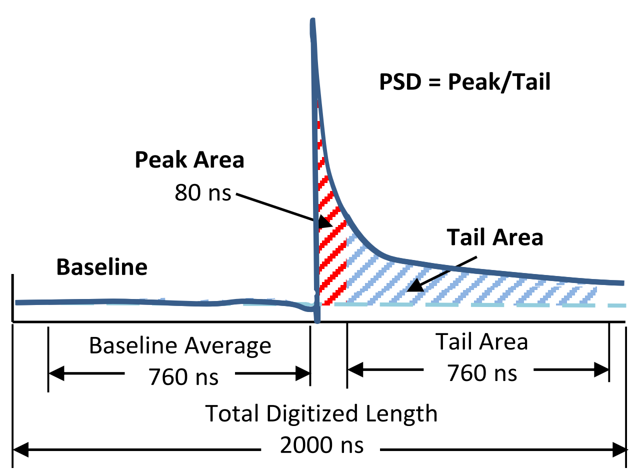

Fig. 4. A schematic demonstrating how the PSD value is calculated from a digitized detector pulse.

While it is possible to use the calculated PSD values exclusively to classify pulse types, it is beneficial to evaluate the pulse information in the two-dimensional space of PSD value versus peak area. In this mapped parameter space two clear regions emerge that provide a strong separation between neutron and photon pulse types, allowing for a high level of accuracy in the classification process. Examples of both a photon-only data set from an isotopic check source (top) and a mixed-particle data set from a spontaneous fission source (bottom) are shown in Fig. 5. At higher peak amplitudes there is a distinct division in particle types in the mixed source data; however, at lower peak values the pulses start to overlap in this parameter space. The plots in Fig. 5 show how a large fraction of these data sets fall into this region of overlap. Hence, applying a peak area threshold to the data to simply discard this somewhat ambiguous region of parameter space would result in the loss of a significant amount of useful data. To overcome this, regions of the parameter space were defined for each detector assembly that both preserve clear areas of separation and reject pulses that fall into regions of high uncertainty in particle origin. These boundaries for the regions selected for the data in Figure 5 are denoted by red lines.

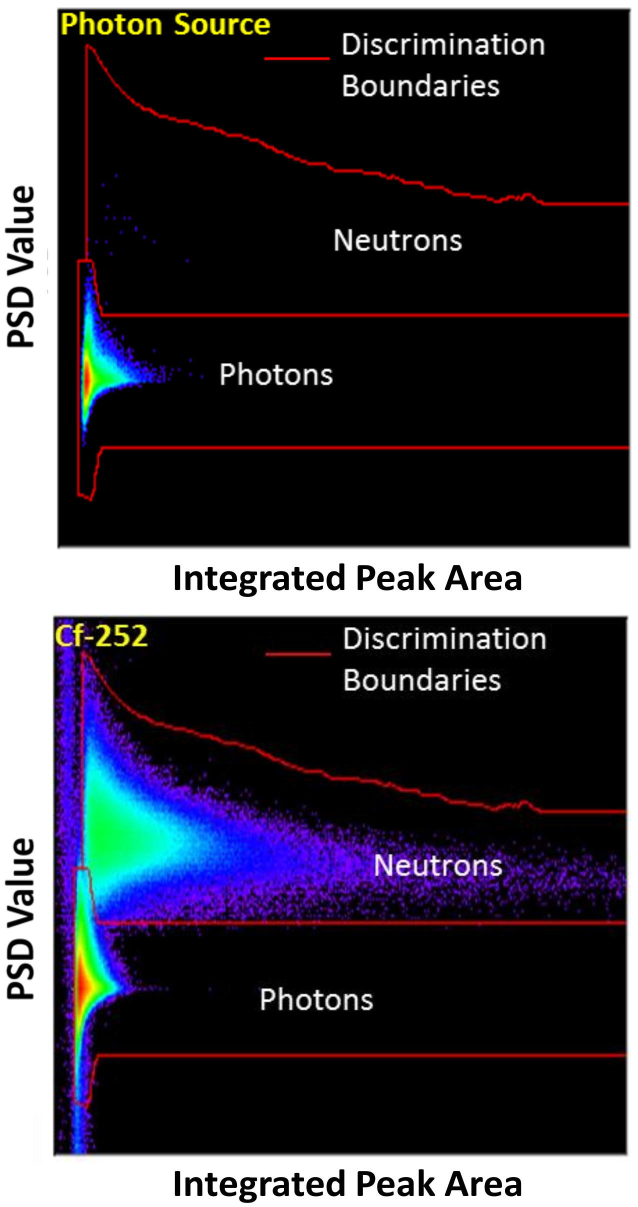

Fig. 5. Two dimensional mapping of the PSD value verses integrated pulse amplitude.

The definition for the prescribed neutron and photon regions in the PSD value versus peak-area parameter space are stored as customizable LUTs on the Struck digitizer card for each detector channel. Detection events are processed by onboard field-programmable gate arrays (FPGA) to provide incident particle-dependent histogram distributions of detection time and integrated. These distributions can be accessed in real time via Ethernet connection. Onboard analysis has the advantages of eliminating the need for post-measurement data analysis and greatly reducing the amount of data that needs to be transferred. While only a single digitizer card was used for preliminary testing of PSD methods, each 16-channel card operates independently allowing the system to be expanded to meet operational requirements through the simple addition of additional cards.

IV. PSD Results

Time-of-flight (TOF) measurements were performed to evaluate the performance of the PSD algorithm. A ^{252}Cf spontaneous fission source was placed 1.16 meters from a ZnS(Ag) detector. A fast plastic scintillator was placed directly adjacent to the source to provide a clock reset signal for the digitizer card.

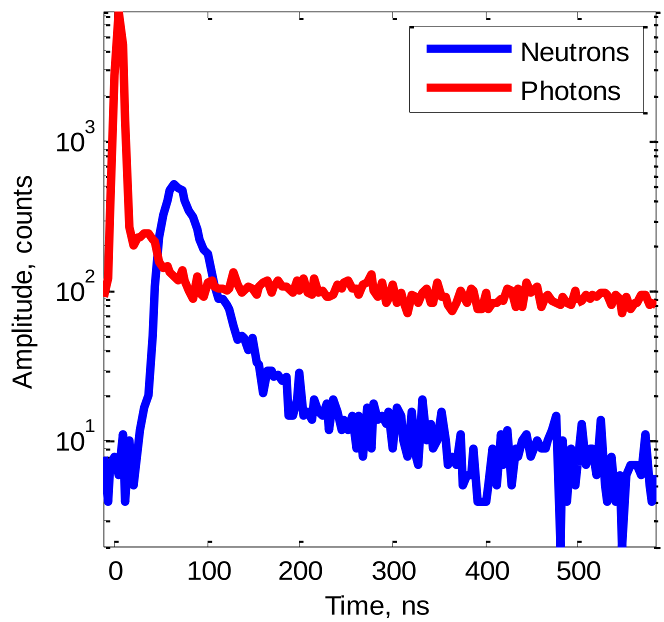

Fig. 6. TOF distributions of a ZnS(Ag) detector with a ^{252}Cf source.

A standard TOF spectrum from prompt fission emissions has two principle features, a narrow photon peak representing the simultaneous arrival of photon emissions, followed by a wider peak later in time that characterizes the velocity-dependent arrival of neutron emissions. Provided that a long-enough distance between the fission source and detector is used, this type of measured spectrum provides a distinct temporal separation of particle types. A plot of the results of this measurement using the pulse classification approach described above is shown in Fig. 6. The digitizer provides particle-dependent timing spectra of detected events which are plotted against each other in this figure. These results show a clear temporal separation in the particle distributions that validates the effectiveness of the particle classification methods using the Struck hardware.

The TREAT hodoscope is expected to measure extremely high levels of radiation, particularly during a transient pulse of the reactor. Therefore, tests were performed to determine the dependency of the PSD method's performance upon count rate. The system's event throughput is fast but is limited by the duration of each pulse. The ZnS(Ag) will scintillate for several microseconds following a neutron interaction; however, only one microsecond before and after a pulse are needed to allow for adequate PSD performance. Therefore, a maximum pulse rate of 500 thousand events per second per detector is expected. This was initially tested using a function generator module to incrementally increase the frequency of a simulated detector signal sent to the digitizer card. The results of this measurement are shown in Fig. 7 and compared to idealized rates obtained by bypassing the particle classification algorithms on the digitizer. The system performed as expected, without losing data prior to reaching a maximum input frequency of just over 500 thousand counts per second. This figure also demonstrates the paralyzable nature of the system, losing increasing amounts of data with increasing input rate beyond the maximum value. (Note: the sample size of the digitization window was decreased in these tests in order operate at higher count rates.) A count rate of 1.7 million counts per second was attained with this method; however, pulse classification reliability was diminished significantly.

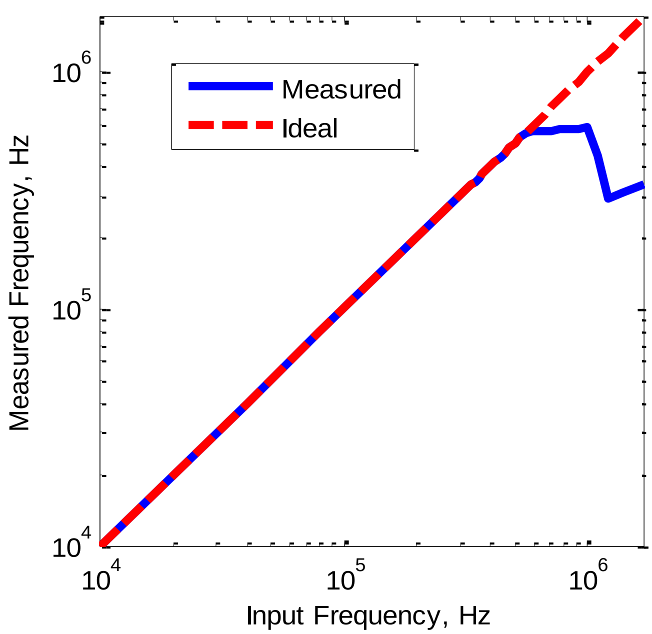

Fig. 7. The system count rate throughput is very fast but is limited by the duration of the pulse. The Measured line (BLUE) shows waveform data measured with the PSD algorithm operation. The Ideal line (RED) shows waveform data measured with the PSD algorithm turned off.

A second series of count rate tests were performed using a radioactive ^{137}Cs source with a well-defined incident dose and moving the detector progressively closer to the source to achieve higher and higher count rates. A maximum throughput of just over 500 thousand counts per second was achieved before the system performance began to degrade, Fig. 8.

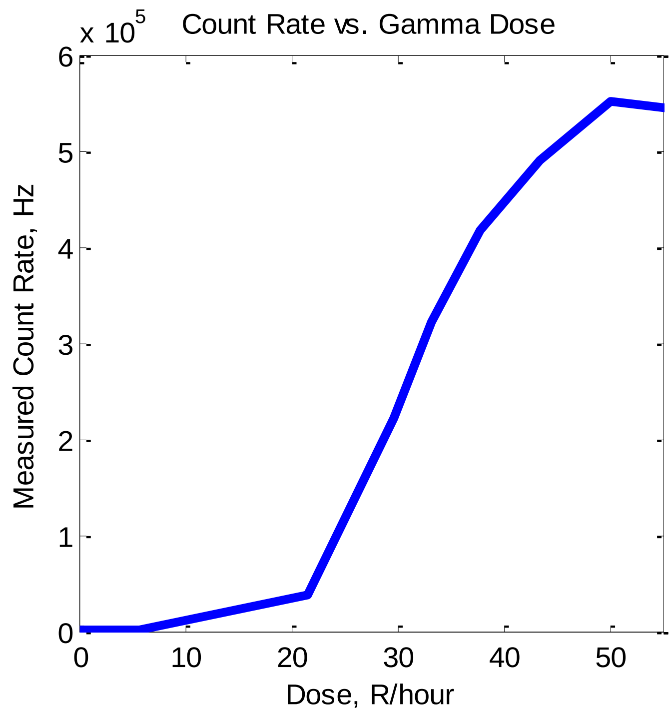

Fig. 8. Measured processed count rate as a function of dose from a ^{137}Cs gamma-ray source.

V. Summary

Sixteen TREAT ZnS(Ag) scintillator buttons used in the original FMMS have been refurbished and tested. A method to differentiate neutrons from photons has been optimized and implemented in a Struck SIS3316 digitizer/FPGA pulse processor. The system now provides real-time read out of separate amplitude and temporal distributions of both neutron and photon events for 16 individual detector channels. Initial testing of the PSD algorithm showed clear and effective particle differentiation up to rates of 500,000 events per second per channel. Each block of 16 channels is autonomous after initial programing and startup with on-demand readout, providing straightforward scalability in blocks of 16 channels.

References

[1] W. F. Hornyak, "A Fast Neutron Detector," Rev. Sci: Instruments, 23, 264 (1952).

[2] G. F. Knoll, Radiation Detection and Measurement (John Wiley&Sons, Inc., New York 2000).