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CHELSI: Recent developments in the design and performance of a high-energy neutron spectrometer

Thomas D. McLean[a,*], Richard H. Olsher[a], Robert T. Devine[a], Leonard L. Romero[a], Anthony Fallu-Labruyere[b], Peter Grudberg[b], Hui Tan[b], Yunxian Chu[b]

[a]Los Alamos National Laboratory, Los Alamos, NM 87545, USA
[b]XIA LLC, Newark, CA 94560, USA

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Abstract

The intrinsic pulse shape discrimination properties of CsI(Tl) form the basis of a high-energy neutron (>20 MeV) spectrometer (CHELSI) currently being developed at LANL that shows promise in satisfying the requirements of an ideal survey meter; lightweight, portable and real time display of dose.

Charged particle spallation products generated in the scintillator via neutron interactions are identified on the basis of pulse shape using digital pulse processing. Conservative estimates of dose rate can be given in real time based on count rates and pulse height distributions. More accurate dose measurements can be done off-line using unfolding methods to analyze stored pulse shape versus energy data.

As a precursor to the development of a portable instrument, data has been obtained using a 1″ × 1″ CsI-based probe and a digital spectrometer. This system has been used to collect data on the 90 m flight path at the LANSCE/WNR facility at an average neutron energy of 335 MeV. The spectrometer has the capability, in addition to storing individual waveforms for later analysis, of recording time-of-flight data and calculating a pulse shape parameter and pulse height for each scintillation event in real time. Combining these data with traditional multichannel analyzer data has yielded a set of empirical response functions with respect to neutron energy. Analysis of the charged particle spectra has yielded an overall average count rate of 0.12 ± 0.02 cps/μSv h for a 1″ × 1″ CsI(Tl) scintillator in this neutron field.

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1. Introduction

With the recent interest in the design and construction of spallation neutron sources for such applications as the transmutation of nuclear waste, an examination of the current state of radiation protection regarding high-energy neutrons is prudent. Existing methods of area monitoring or surveying such as rem meters, foil activation-based methods or Bonner spheres are not completely satisfactory for a variety of reasons. An ideal instrument would be lightweight, portable and give a real time indication of dose rate.

A program to develop such an instrument is underway at LANL [1]. Nicknamed CHELSI, the instrument is based on the well-known pulse shape discrimination properties of CsI(Tl) [2–5]. Incident neutrons above 10 MeV produce charged particle spallation products that, in turn, generate light emission in the scintillator as they slow down. These waveforms can be analyzed for pulse shape (i.e. particle type) and pulse height in real time using digital pulse processing.

Conservative estimates of dose rate can be displayed during field measurements solely on the basis of charged particle count rate and a rudimentary knowledge of their

*Corresponding author. Tel.: +1 505 665 9944; fax: +1 505 665 7686.
E-mail address: tmclean@lanl.gov (T.D. McLean).

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pulse height distribution. For areas with elevated readings, better estimation of neutron fluence and dose can be gained by off-line deconvolution of the stored charged particle data. This approach requires that the scintillator response function be well known. To this end, time-of-flight (ToF) data has been collected at the LANSCE/WNR facility. These measurements were also an opportunity to evaluate and compare on-line pulse shape discrimination algorithms with the off-line analysis of stored waveforms.

2. Facility description

The irradiations at LANSCE were done on the 90 m flight path at the Weapons Neutron Research (WNR) facility. This flight path, located at an angle of 15° relative to the tungsten spallation target, is the longest beam line at LANSCE. Shielding (copper, lead and polyethylene) was inserted in the beam path to both harden the spectrum and reduce the neutron and gamma fluence at the detector location. In addition, stainless steel collimators were placed at the beam exit port to further limit the fluence.

The beam time structure consisted of 590-μs-long macro pulses emitted at a repetition rate of 100 Hz. Each macro pulse was divided into a train of micro pulses separated by 1.8 μs. Average beam current at the tungsten target was about 3.2 μA.

3. Experimental details

The detector was based on a 1″ × 1″ CsI(Tl) scintillator coupled to a Hamamatsu R6095 PMT as described previously [1]. The anode signal was fed to a current-to-voltage converter to preserve signal shape. This signal was processed using a Polaris™ digital spectrometer, controlled by a host laptop computer via an USB interface, operated in either of two basic modes as described below.

The first mode was as a traditional multichannel analyzer. Typically, 64 K channels were used to obtain satisfactory resolution of the low energy gamma calibration lines. Calibration was done using ^{60}Co and ^{137}Cs check sources and the 4.43 MeV ^{12}C prompt gamma ray from a PuBe source.

In the second mode of operation (list mode), individual waveforms were digitized and stored for later pulse shape analysis. Each waveform was also analyzed on-line for pulse shape and pulse height. In addition, ToF data was recorded and stored with the waveform data along with the results of the on-line analysis of shape and energy. The ToF start signal was provided by the scintillation event while a TTL pulse, derived from the master micro pulse timer, was fed into the sync input of the Polaris spectrometer to provide the stop signal. Timing resolution was limited to 25 ns, a consequence of the 40 MHz clock speed of the spectrometer, permitting only crude resolution ($\Delta E \sim 150$ MeV) of the highest energy neutrons.

ToF-tagged ^{238}U fission chamber [6] data was collected concurrently with the scintillator data to determine beam fluence from which incident dose was calculated [7].

To bridge the large difference in the fission chamber efficiency and that of the CsI scintillator, a SWENDI rem meter [8] was employed as a beam monitor. Positioned about 1.5 m directly behind the CsI probe, SWENDI was calibrated (net counts per fission event) through a long run against the fission chamber. The delivered fluence during the relatively short scintillator runs could then be determined from the SWENDI counts.

4. Results

Analysis of the ^{238}U fission chamber data with 10 cm of copper, 20 cm of polyethylene and 10 cm of lead in the beam line yielded the neutron spectrum shown in Fig. 1. All the data discussed below were taken with this shielding configuration.

The average beam fluence ($E > 10$ MeV) was calculated as $2.6 \pm 0.3 \times 10^3$ neutron/cm^2 s at the detector location with a corresponding average $H^*(10)$ dose rate of 3.3 ± 0.3 mSv/h [7]. A fluence-weighted mean energy of 335 MeV was calculated for the spectrum.

Calibration of SWENDI against the fission chamber established a counting efficiency of 16 ± 1 neutron/cm^2 per SWENDI count. For short runs, the incident fluence was calculated from the SWENDI data using this conversion factor.

Fig. 2 shows the pulse shape versus pulse height plot determined from an off-line analysis of 50,000 waveforms recorded in list mode. A pulse identification index (PID) was calculated by dividing the signal integrated over a fast timing window by the total pulse energy. As a result, higher PID values correspond to faster pulses. Optimum pulse shape discrimination was obtained by setting the width of the fast timing window to 1.2 μs.

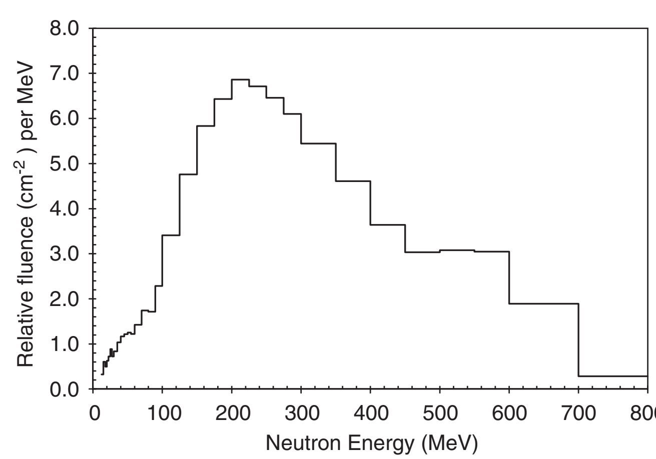

Fig. 1. Neutron spectrum on 90 m flight path as measured by fission chamber. Beam line contained 10 cm of copper, 20 cm of polyethylene and 10 cm of lead.

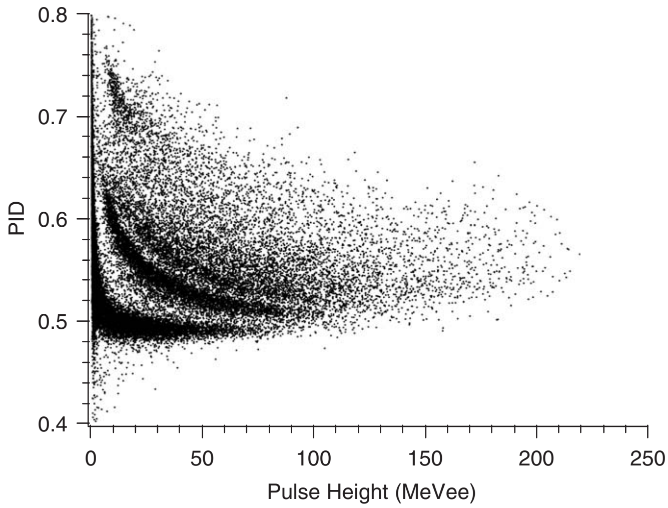

Fig. 2. Offline analysis of pulse shape and energy. All events are shown.

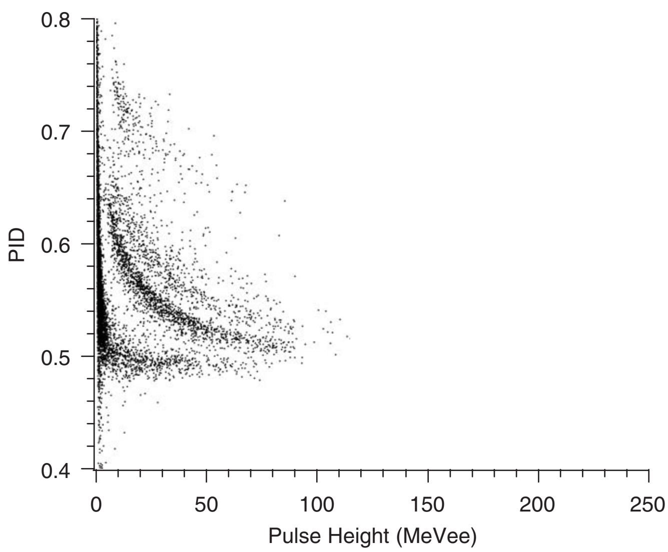

Fig. 3. Off-line analysis of pulse shape and energy. Only those events initiated by neutrons between 100 and 130 MeV are shown.

The dark band in Fig. 2 with PID values near 0.5 is due to gamma events. Above the gammas lie the charged particle events where only the proton band, positioned just above the gamma band, is readily discernible in Fig. 2.

Fig. 3 shows the PID vs energy (PID_E) plot initiated, based on the ToF data, by neutrons between 100 and 130 MeV. At these neutron energies the gamma and individual charged particle bands are more evident than in Fig. 2. This is because as neutron energy increases, the probability of two or more charged particles being released simultaneously also increases. When these multi-particle events occur, the resultant pulse shape has a composite PID value (and energy) and will, as demonstrated in Fig. 2, tend to fill the gaps between the single particle bands.

The on-line pulse discrimination results were not as impressive as the off-line results. For example, the proton and gamma bands merged at pulse energies above

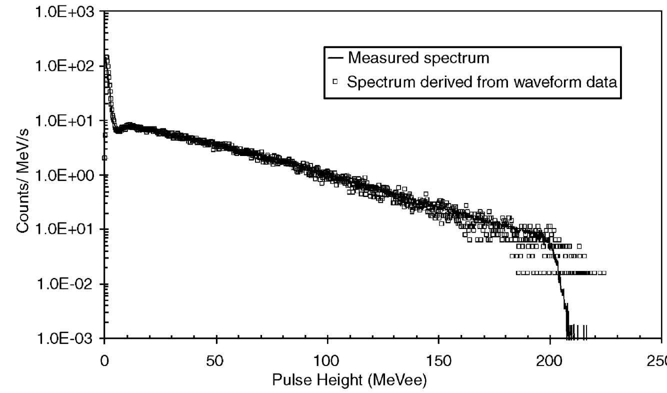

Fig. 4. Comparison of the measured MCA spectrum and one derived from waveform data recorded under the same conditions. The waveform-derived spectrum has been scaled to match the total number of counts in the MCA run.

50 MeVee. In the on-line analysis, the signal is differentiated and a discriminator used to infer the time reference for the PID calculation. Jitter in this timing signal is manifested as a broadening of the PID result, an effect that is more apparent with increasing pulse energy. Improvements to the on-line analysis firmware are planned to enhance future performance.

The pulse height data shown in Fig. 4 compares the spectrum recorded in MCA mode with that derived from an analysis of the waveform data (i.e. from projecting the PID_E data in Fig. 2 onto the energy axis). The excellent agreement demonstrates that, when operated in list mode, the spectrometer faithfully samples the entire range of pulse waveforms.

The upper range of the spectra shown in Fig. 4 are truncated due to signal saturation. When operated at lower gain, the spectrum extended as far as 240 MeVee. This upper limit is in excess of the amount of light that can be produced by a single particle (e.g. for protons, about 90 MeVee in a $1'' \times 1''$ CsI scintillator) but is consistent with integrated light emission from multi-particle spallation events.

5. Discussion

MCA and list mode (waveform and ToF) data recorded under identical conditions can be combined to calculate charged particle count rate per unit fluence rate as a function of neutron energy. List mode data yields the relative contribution for any region of the PID_E plot to the MCA spectrum. Normalizing this data to the dead time-corrected MCA spectrum (as shown in Fig. 4) and to the fission chamber data allows the calculation of counting efficiency, for any subsection of the PID_E plot, per unit fluence (or dose) as a function of neutron energy. For example, over the charged particle region of the spectrum, a combined count rate of 400 cps was calculated for the data shown in Fig. 4. This translates to a total charged particle count rate of 0.15 ± 0.02 cps per unit fluence rate or

0.12 ± 0.02 cps/μSv h for a $1'' \times 1''$ CsI scintillator in the neutron field shown in Fig. 1.

Segregating the PID_E data on the basis of ToF is the initial step in the generation of a set of empirical response functions. It is further required that the charged particle region in each individual PID_E data set be binned to obtain a discrete representation of the PID_E data. These response functions can then be applied to unfold any similarly partitioned PID_E plot (i.e. a composite plot showing all events) to reveal the incident neutron spectrum. Efforts are now underway to apply this analysis strategy.

A prototype portable instrument based on a $2'' \times 2''$ CsI(Tl) scintillator for improved detection efficiency is being assembled for evaluation. The probe includes a low-power bias supply, rechargeable batteries and a μDXP card[1] loaded with firmware for real time pulse shape and energy analysis. This data, along with input and output count rate information, will be transmitted via an RS232 interface to a PDA for on-line calculation and display of neutron dose rate above 20 MeV. The data will also be stored for subsequent unfolding off-line.

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