Measurement of the Neutron Travel Time Distribution Inside a Neutron Monitor

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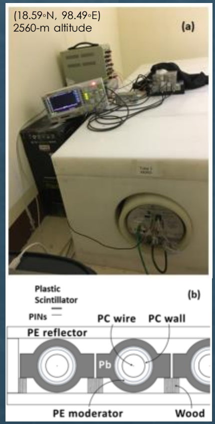
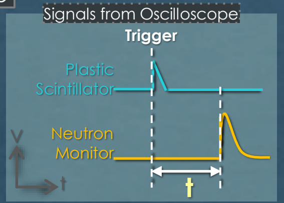
In a **neutron monitor**, atmospheric secondary particles from cosmic ray showers interact in lead to produce neutrons that are detected in proportional counters. We used **charged particle detectors** to provide a timing trigger for measurement of the **travel time distribution** of such neutrons, and compare with **Monte Carlo simulations**.

Experimental Setup





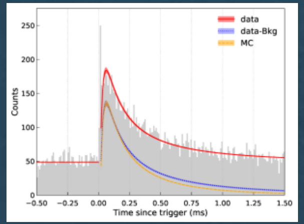
Experimental setup, with charged particle detectors (**scintillator and Si PIN array** as prototype satellite detector components) placed on top of **the Princess Sirindhorn Neutron Monitor (PSNM)** at the summit of Doi Inthanon, Thailand. The signal from charged particle detector was used as a **trigger** to collect the waveform of the signal from the neutron monitor by oscilloscope. The trigger signal was set to be detected at 0.5 ms of total 6 ms time window of the oscilloscope.

The **travel time** since the trigger (**t**) was calculated from the wave form in post analysis.

Simulation

The interaction of protons and negative and positive muons at ground level with the 18NM64 of PSNM was simulated using **Fluka** (version 4-1.1). The particle spectra from EXPACS 4.09 were injected downward from 10 μm above the scintillator. The travel time and energy deposited in the proportional counter above 0.44 MeV was taken into account, weather it was produced by ^{10}B fission or the ionization due to the charged particle .

Diffusion-Absorption Model



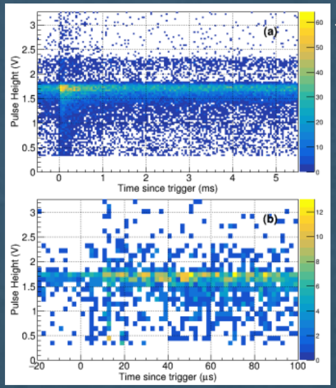
Experimental travel time distribution for all NM pulses over $-0.5 \le t < 1.5$ ms, together with fits to experimental data (red band), experimental data subtracting a uniform background due to chance coincidences (blue band), and normalized simulation data (orange band) using a 2D neutron diffusion-absorption model, for x and y directions perpendicular to the proportional counter wire:

$$n \propto \frac{1}{t} exp\left(-\frac{x^2+y^2}{4Dt}\right) exp(-\alpha t)$$

n : neutron areal density
D : neutron diffusion coefficient
x,y : projected position
α : absorption rate

The error bands represent the 1-σ uncertainty from the fits. In both cases the fits were to all data during $0.02 \le t < 5.5$ ms for a time bin width of 10 μs, excluding the initial spike of pulses measured promptly after the charged-particle trigger. **The diffusion-absorption model** provides a very good **match to the peak and tail of the neutron propagation time distribution**, and the results from experimental and simulation data are quite consistent, especially near the peak of the distribution.

Overview of Travel Time Distribution

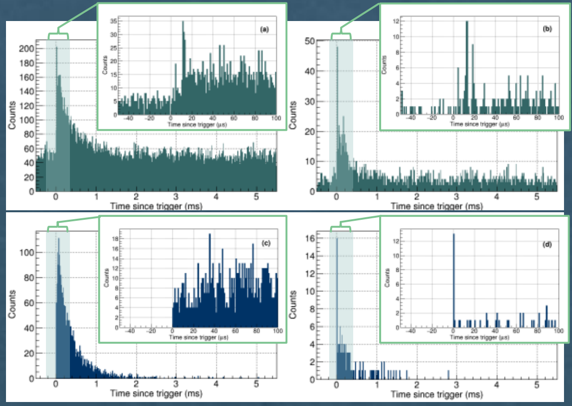


The distribution of pulse height and time relative to a charged particle trigger for each pulse in PSNM Tube 1 is shown in figure (left), (a) for all data ($-0.5 \le t < 5.5$ ms) and (b) for $-20 \le t < 100$ μs.

Timing and pulse height data from PSNM Tube 1 were analyzed for time intervals from −0.5 to 5.5 ms relative to 165,500 charged- particle triggers, which were found to contain 35,661 NM pulses.

In (a), a pulse height distribution characteristic of neutron- induced fission of ^{10}B in the proportional counter(PC), mostly at pulse heights $1 \le PH < 2.5$ V, is observed at all times. This includes background chance coincidences, unrelated to the charged- particle trigger, that are uniform in time. The density of neutron counts is strongly enhanced shortly after the charged-particle trigger at time t = 0. Note that the distribution in pulse height of background counts is consistent with neutron induced fission of ^{10}B in the PC, with a main peak at PH ≈ 1.7 V.

In (b), there is additional group of prompt pulses during $0 \le t < 20$ μs at low pulse height, especially at PH < 1 V, which we attribute to charged particle ionization signals in the proportional counter.



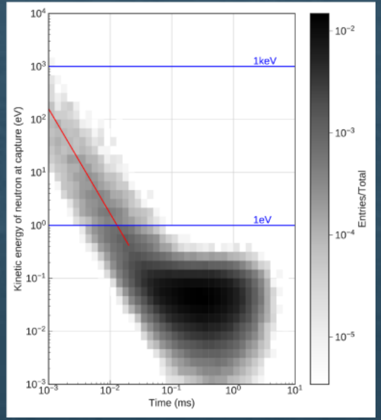
Distributions in time t (relative to a charged-particle trigger) of pulses in PSNM Tube 1 with $-0.5 \le t < 5.5$ ms for (a) high pulse height, PH ≥ 1 V, from neutron pulses **and (b) low pulse height, $0.326 \le PH < 1$ V**, representing wall-effect neutron pulses and charged-particle ionization, **as well as Monte Carlo simulation results for energy deposition ranges corresponding to (c) high pulse height and (d) low pulse height.** Neutron pulses are identified from neutron-induced fission of ^{10}B in the proportional counter. Simulated pulses are all neutron pulses, with the exception of the spike at t = 0 in panel (d), which is mainly due to charged-particle ionization.

Note that the experimental distributions include a uniform background due to NM pulses unrelated to the charged-particle trigger, which are not included in the simulation. The experimental and simulated distributions are in good agreement, except that the experimental distribution (a) shows a spike of promptly detected neutrons at $0 \le t < 20$ μs that is not present in the simulated distribution (c).

The inserts show the distribution for $-50 \le t < 100$ μs. During $0 \le t < 20$ μs and there is an enhanced rate of promptly detected neutron pulses at high pulse height in the experiment (a) but not for the simulation (c). At low pulse height, the pulse is much more prominent, and the simulated pulses (d) during the spike at t = 0 are mostly due to charged-particle ionization and at later times entirely wall-effect neutron pulses.

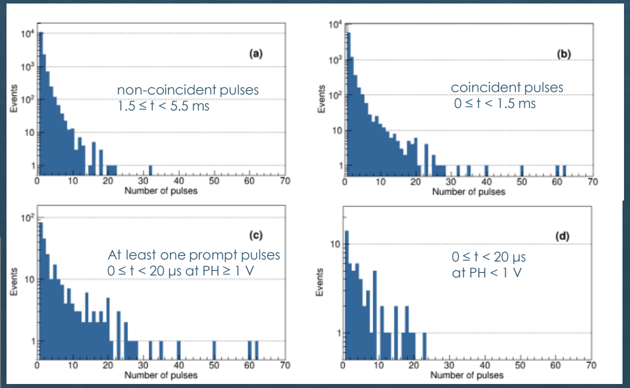
The simulation confirms the interpretation that the strongly enhanced rate of pulses at $0 \le t < 20$ μs and low pulse height in (b) can be attributed mostly to charged-particle ionization, and pulses at $t \ge 20$ μs can be attributed to wall-effect neutrons.

Prompt NM Pulses and Multiplicity



Simulated distribution of neutron capture events as a function of kinetic energy of the neutron when captured and time of capture relative to charged-particle injection just above the scintillator. The grand majority of neutrons are thermal when captured, yet captures at higher energy do occur at early times, t < 20 μs. For these, **the neutron energy** is related to time with a best-fit power-law (red line) of slope −2.0, which **corresponds to a time-of-flight** relationship over a distance s = 18 cm. Blue lines correspond to neutron energies of 1 eV and 1 keV.

Multiplicity distributions of pulses in PSNM Tube 1. It can be seen that prompt pulses are frequently associated with events of unusually high multiplicity, e.g., from charged secondary particles of particularly high energy.



Note that in a case of very high multiplicity of NM pulses, it is quite possible that there were pulses due to more than one atmospheric secondary particle from the same primary cosmic ray shower.

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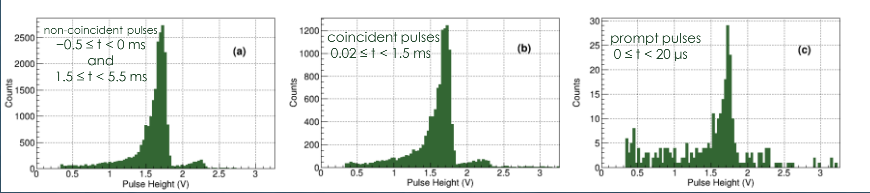
Time-Selected NM Pulse Height Distributions



Pulse height distributions of the experimental pulses from PSNM Tube 1. (a) The distribution of non-coincident pulses is typical for neutron detection by a $^{10}BF_3$ proportional counter. (b) The distribution of coincident pulses, excluding prompt pulses, is similar with a slight relative enhancement of pile-up at PH > 2.5 V and at pulse heights below the peak. **(c) The distribution of prompt pulses is quite different, with a strong relative enhancement of pile-up and also of counts at PH < 1 V; we attribute the latter to charged-particle ionization.**

Conclusion

- ❖ The travel time distribution from both the experimental setup and Monte Carlo simulations of atmospheric secondary particle detection was measured and characterized.
- ❖ We confirm a known travel time distribution with a peak (at ≈70 μs) and tail over a few ms, dominated by neutron counts.
- ❖ This distribution was fit using an analytic model of neutron diffusion and absorption, for both experimental and Monte Carlo results.
- ❖ We identify a group of prompt neutron monitor pulses that arrive within 20 μs of the charged-particle trigger, of which a substantial fraction can be attributed to charged-particle ionization in a proportional counter, according to both experimental and Monte Carlo results.
- ❖ The prompt pulses are associated with much higher mean multiplicity than typical pulses.
- ❖ These results validate and point the way to some improvements in Monte Carlo simulations and the resulting yield functions used to interpret the neutron monitor count rate and leader fraction.

For detailed discussion, see QR code at the top