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# Portable spectroscopic fast neutron probe and $^{3}He$ detector dead-time measurements

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ABSTRACT

This paper presents dead-time calculations for the Portable Spectroscopic Fast Neutron Probe (N-Probe) using a combination of the attenuation law, MCNP (Monte Carlo N-particle Code) simulations and the assumption of ideal paralyzing and non-paralyzing dead-time models. The N-Probe contains an NE-213 liquid scintillator detector and a spherical $^{3}He$ detector. For the fast neutron probe, non-paralyzing dead-time values were higher than paralyzing dead-time values, as expected. Paralyzing dead-time was calculated to be 37.6 μs and non-paralyzing dead-time was calculated to be 43.7 μs for the N-Probe liquid scintillator detector. Dead-time value for Canberra $^{3}He$ neutron detector (0.5NH1/1K) was also estimated using a combination of subcritical assembly measurements and MCNP simulations. The paralyzing dead-time was estimated to be 14.5 μs, and the non-paralyzing dead-time was estimated to be 16.4 μs for $^{3}He$ gas filled detector. These results are consistent with the dead-time values reported for helium detectors.
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## 1. Introduction

Many techniques have been developed for detecting and measuring the uncharged neutron since its discovery in 1932. One of the most prevalent neutron detectors is the organic liquid scintillation detector (e.g., NE-213). These detectors are frequently used in nuclear experiments for their good energy resolution and high detection efficiency for neutrons and photons (Verbinski et al, 1968; Harvey and W/Hill, 1979). Using pulse shape discrimination (PSD) techniques, liquid scintillation detectors allow for the separation of the neutron and photon signals. This technique is based on the difference in scintillator response to neutron and photon events (Yousuke et al, 2000). Since the neutron is not a charged particle, it does not ionize the scintillation material directly. It can be generally detected through nuclear interactions that produce energetic charged particles. Fast neutron detection relies on the production and detection of protons from (*n,p*) reactions within the detector. Therefore, hydrogen-rich materials are typically used as the detector material (Knoll, 2010a). The most commonly used scintillator for fast neutron detection and spectroscopy is the NE-213 liquid scintillator produced by Nuclear Enterprises Limited. The most significant advantage of this scintillator is its excellent pulse-shape discrimination properties compared to other scintillators (Karlsson, 1997).

$^{3}He$ gas proportional counters are common neutron detectors best suited for thermal neutron detection since the $^{3}He(n, p)$ reaction is attractive for thermal neutron detection. $^{3}He$ counters are not suitable for operation in the Geiger-Müller region since there is no capability to discriminate the pulses produced by photon interactions (Tsoulfanidis and Landsberger, 2011). The neutrons are captured by the $^{3}He(n, p)^{3}H$ reaction, producing a tritium and a proton with a *Q*-value of 764 keV. For this reaction, the energy dependent cross section is one of the well-recognized standards in neutron measurements. Since the tritium and proton are charged ions, both are usually be recorded by the proportional counter (Krane and Baker). Another widely used detector for thermal neutrons is the $BF_3$ proportional detector. Boron trifluoride behaves as a proportional gas and the target for thermal neutron conversion into secondary particles. Enriching the $^{10}B$ in the gas can make the detector up to five times more efficient (Knoll, 2010b).

Bubble Technology Industries (BTI) has manufactured a portable neutron scintillation spectrometer (N-Probe) with potential applications at nuclear reactor facilities, waste processing operations, and spent fuel storage areas (Ing et al, 2007). Fig. 1 shows the N-Probe detector which contains a 5 cm by 5 cm NE-213 liquid scintillator detector to record fast neutrons between 800 keV and

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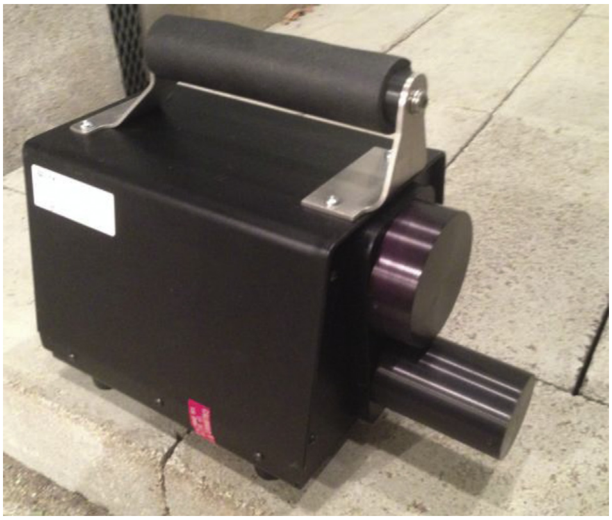

**Fig. 1.** N-Probe fast and thermal neutron spectrometer (Ing et al, 2007).

20 MeV, as well as a spherical $^3$He detector to record low energy neutrons from 0 to 1.5 MeV (Mobile Microspec Operational Manual, 2009). Sophisticated proprietary pulse-shape discrimination is used to remove undesirable photon counts for the NE-213 liquid scintillator detector. Liquid scintillator and $^3$He detectors work simultaneously and energy distributions from both can be seen during the measurements. The detector's software merges information from the two detectors to generate a single neutron energy spectrum. One of the significant advantages of the N-Probe is that it provides both the neutron energy spectrum and the total neutron counts for fast and thermal neutrons.

Scientists have been working on dead-time problems for radiation detectors since the 1940s. In any radiation counting system, a minimum amount of time must separate two events before they can be measured independently. This minimum time separation is referred to as the counting system's dead-time (Muller, 1973). The intrinsic properties of the detector and the pulse processing circuitry's characteristics are the sources of dead-time. Researchers have been working on improving the detector dead-time model which can implicitly characterize a detection system's behavior while reducing counting errors (Muller, 1991; Stever, 1942).

There are two commonly known dead-time models: the "Paralyzing" and the "Non-paralyzing" models. In reality, detection systems fit neither of these idealized models perfectly, instead real detector's behavior falls somewhere between the two models (Feller, 1948). The paralyzing model is mathematically expressed by Eq. (1), where $m$ is the measured count rate, $n$ is the true count rate and $\tau$ is dead-time. This model assumes that each event during the dead-time will reset it to a fixed duration, thus extending the dead-time. The dead-time extension depends on the count rate.

$$m = ne^{-n\tau} \tag{1}$$

According to the non-paralyzing model, dead-time is fixed after each detected event, and all events occurring during dead-time are lost. The fraction of time during which a detector is sensitive is 1-$m\tau$. Therefore, the fraction of the true number of events that can be recorded are simply Eq. (2) (Feller, 1948);

$$m = \frac{n}{1 + n\tau} \tag{2}$$

The dead-time of the N-Probe detector is not provided by the manufacturer; BTI, and there is no other study published on the N-Probe detector' dead-time. In this study, the dead-time of the BTI N-Probe (NE-213 Liquid scintillation) was examined using different thicknesses of Plexiglas at the Missouri University of Science and Technology Research Reactor (MSTR). Furthermore, the dead-time of the Canberra 10 mm diameter $^3$He tube detector (Tucker et al., 2016) was calculated by comparing measured counts from different locations in the subcritical assembly at MSTR with MCNP simulations. The dead-time calculations are provided for both the paralyzing and non-paralyzing model assumptions for the fast neutron detector (N-Probe) and the Canberra 10 mm diameter $^3$He tube detector.

During all experiments, the reactor operated at 5 kW power for a standardized neutron flux from the beam port. The macroscopic cross section of Plexiglas was calculated for fast neutrons using the fast neutron detector (N-Probe). For the total macroscopic cross section measurements the flux was low, and hence the effect of the detector dead-time can assumed to be negligible at 5 kW reactor power. The neutrons were attenuated by different thicknesses of Plexiglas and counted by the detector in front of MSTR beam port.

For $^3$He detector dead-time calculations, the MSTR Subcritical Assembly was filled with water and its plutonium-beryllium (PuBe) neutron source was used for measurements. The MSTR Subcritical Assembly was also simulated using MCNP code for all positions. Using the combination of measurement and simulation results, the dead-time of $^3$He detector was calculated.

## 2. Experimental design

### 2.1. Dead-time experiment for N-Probe fast neutron detector

The MSTR is a swimming pool type reactor licensed to operate at 200 kW. The beam port, which is 15.24 cm in diameter and 6.45 m long, was used to take fast neutron measurements (http://nuclear.mst.edu/re). A special 2-cm-diameter collimator was used for the neutron beam from the beam port to the Plexiglas. During the experiment, the operation of the detector and measurement was controlled remotely by a computer to avoid any radiation exposure. Fig. 2 shows the experimental set-up of the system to measure fast neutrons with N-Probe detector in the beam port room at MSTR. This set-up allowed for a beam of neutron with post moderation energy distribution to be available for measurement.

Fast neutron measurements were first taken with no plexiglass. A 0.5-cm-thick layer of plexiglass was then placed between the detector and collimator. The neutron measurements were taken from 0 to 3.0-cm-thick layers of plexiglass using thickness intervals of 0.5 cm. Measurements with and without plexiglass were taken for ten minutes with a constant flux/beam intensity at 5 kW power. With the reactor still at 5 kW, the beam port was closed to replace the plexiglass after each measurement.

**Fig. 2.** Illustration of experimental setup.

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