

Reliable Neutron Detection

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Abstract

Neutrons are a telltale sign of nuclear reactions. Thermonuclear fusion, fission, and spallation are the three most common processes typically associated with neutron emission. Yet there is no shortage of novel theoretical concepts pertaining to ‘new physics,’ which may result in neutron emission. ‘Cold fusion’ and ‘condensed matter nuclear fusion’ are two such examples. For decades, radiation detection has been a primary tool for experimental verification of such new concepts. While neutron detection per se is well understood, a review of the literature reveals a troubling trend: a profound lack of understanding of its fundamentals among many authors, which has led to the publication of unreliable, low-quality data. The problem becomes even worse when low levels of neutron counts are presented. Great care involving the elimination of systematic errors backed by statistical analysis must accompany such results to prove that the observed signal is indeed in excess of background. Yet, more often than not, such care is missing. This is the problem we aim to address in this paper. We present a novel neutron detection system, NEUTRON-X, designed to be resilient against common electromagnetic interference. We further introduce a cost-effective MCA-PRO hardware architecture, supported by the PulseCounter Pro software, that enables real-time acquisition of detector signals, individual pulse auditing, digital pulse processing, and multi-channel analysis (MCA). Together, NEUTRON-X, MCA-PRO, and PulseCounter Pro form a platform for reliable neutron and gamma detection that is inexpensive and easy to use. To complete the discussion, we outline the neutron detection best practices and demonstrate their application in a specific use case. The objective of this publication is to establish a ‘gold standard’ for the detection of low levels of neutron radiation and encourage its adoption for the sake of the production of high-accuracy neutron counts, and thus accelerate the process of discovery.

1. Introduction

Reliable neutron detection is one of the key problems in experimental nuclear science, since neutrons are telltale signs of nuclear reactions. Thermonuclear fusion, fission, and spallation are the three most common processes typically associated with neutron emission. Yet there is no shortage of novel theoretical concepts pertaining to ‘new physics,’ which may result in neutron emission. For example, Czerski theorizes that the DD fusion cross section in both solid and gaseous states at low energies can be enhanced by nuclear resonances¹. Peter Hagelstein, arguably the most prolific contributor to novel theoretical models of condensed matter nuclear science, recently published an extensive review of the composite quantum particle hypothesis², which provides a theoretical mechanism for various modes of coupling of external fields and

influences to nuclear constituents. Such coupling is necessary to boost the otherwise exponentially small fusion cross-section, which in conventional hot plasma physics is chiefly determined by the center-of-mass energy, making it effectively zero at room temperature.

Currently, there is no consensus among theorists on the most likely mechanism for the increase in DD fusion probability in solids; multiple mechanisms may be at play. Metzler et al. reviewed known theoretical mechanisms, including Coulomb screening. They showed how various factors can act together to enhance the DD fusion reaction rate by 40 orders of magnitude, thereby enabling fusion detection at room temperature³.

The exciting, even if controversial, theoretical developments go hand in hand with experiment. While numerous nuclear science experiments have been conducted in recent decades, many suffered from inadequate detection techniques. The notable experiments that speak to the reality of 'new physics', or at least to the incompleteness of our understanding of nuclear processes occurring in condensed matter, are as follows.

In 2013, Agafonov et al. reported in PRL neutron emission during high-voltage discharges^{4,5}; although spallation is considered the most likely cause⁶, the exact mechanism of neutron emission remains unknown⁶.

In 2023, Gotzmer et al. reported on the observation of nuclear particle emission using CR-39 track detectors during Li–Pd–Rh–D₂O electrochemical experiments at elevated voltage⁷. While CR-39 detectors are resilient and time-tested, they are a far cry from the state-of-the-art nuclear particle detectors that ought to be used to study and characterize the purported nuclear emissions in real time.

In 2024, Czerski et al. observed thermal deuteron-deuteron fusion in ion tracks using PIPS detectors⁸. While PIPS charged particle detectors are significantly more sensitive than CR-39, neutron detection (which was missing) is considered to be a 'gold standard' for establishing the reality of nuclear fusion.

In 2025, a 15% increase in the DD fusion rate in electrochemically loaded palladium bombarded by deuterium ions was reported in Nature⁹. The neutron counts were measured using liquid scintillators, which are well-suited for the detection of fast neutrons, although the data captured with such detectors requires complex and time-consuming 'unfolding'¹⁰.

In 2024, we also reported the observation of significant, 10,000x above-background, neutron emission during acoustic cavitation of a D₂O + TiD_x emulsion/suspension in mineral oil¹¹. These observed neutron counts exceeded 1,500 CPM and were measured using a bank of ³He proportional counters.

The mounting evidence for neutron emission under atypical conditions necessitates *reliable detection* of minute neutron counts, as neutron detection is the primary tool for experiment design and optimization based on the magnitude of the observed nuclear emission, even when it is vanishingly small.

By 'reliable' neutron detection, we mean a detection methodology that:

1. allows for straightforward identification of erroneous counts caused by noisy signals, detector malfunction, or common sources of systematic errors (such as gamma rays or other charged particles);
2. is immune to common sources of RF interference that pollute and distort detector signals due to capacitive coupling, magnetic coupling, or ground loops.

In this work, we address this critical problem by introducing a novel hardware and software system – NEUTRON-X – for reliable neutron detection. The NEUTRON-X system is compact, inexpensive, easy to use, and virtually immune to common sources of RF interference.

2. Neutron Detection Basics

Most neutron detectors produce a current pulse corresponding to a detected particle, with large pulses corresponding to neutrons and smaller pulses corresponding to X-rays/gammas, or other interfering particles¹². While there are many types of neutron detectors, such as ⁶Li-loaded glass scintillators¹³, boron-rich solid-state detectors¹⁴, and different kinds of crystalline¹⁵ and liquid organic scintillators¹⁶, in this paper, we focus on proportional counters. Specifically, on ³He-filled proportional counters, which are characterized by the highest sensitivity to thermal neutrons. While shortages of ³He gas have temporarily driven proportional counter prices up, the concern appears short-lived, as numerous ³He-filled proportional counter tube configurations are available in the U.S. from Reuter-Stokes (www.reuter-stokes.com) and LND (www.lndinc.com), with some detector models priced at approximately \$1,000 USD. These devices produce current pulses on the order of pC/neutron and thus require charge-sensitive preamplifiers to amplify the signal, converting it into a voltage step suitable for digital pulse processing¹⁷.

The industry-standard algorithm for digital pulse processing is trapezoidal filtering¹⁸, which converts slow, exponentially decaying voltage steps into triangular (or trapezoidal) pulses suitable for counting and multi-channel analysis. Because, under most circumstances, neutron counts are low, the probability of pulse pile-up due to the fronts of the multiple neutron events overlapping is relatively small and thus represents a much less significant problem than in gamma detection, where typical count rates are much higher.

As such, reliable neutron detection, for the most part, represents a purely methodological problem that can be fully addressed by statistical analysis coupled with careful control of systematic errors. In this paper, we lay down a foundation for such a methodological approach.

2.1 Detector Sensitivity

The ³He neutron detector sensitivity depends almost entirely on the solid angle covered by the detector. Therefore, placing the detector as close as possible to the neutron source yields the highest count rate. From the standpoint of detector sensitivity, ³He-filled proportional counters have nearly identical thermal-neutron sensitivity per unit area: 77% at 4 atm fill pressure¹² and approach 100% at higher fill pressures.

Neutron detector sensitivity is typically expressed in CPS/nv, where nv is the measure of neutron flux, $nv = \text{neutrons}/(\text{s cm}^2)$. Thus, the CPS/nv characteristic of a ^3He proportional neutron counter is chiefly determined by the detector size. Therefore, larger detectors and multi-detector banks with greater solid angle coverage are preferable for measuring weak neutron signals.

3. RF Interference

The biggest problem in neutron and gamma detection is electromagnetic interference, manifested as RF noise and ground loops. RF interference often introduces artifacts into detector signals, which can be mistaken for legitimate neutron events when digital pulse processors (DPPs) shape and analyze the noisy signals. Fortunately, it is easy to tell the RF interference apart from a legitimate neutron pulse by visual examination of the detector signal: preamplified neutron pulses correspond to voltage steps with slow exponential decay (Fig. 1), while RF interference typically (but not always) corresponds to high-frequency oscillations (Fig. 2).

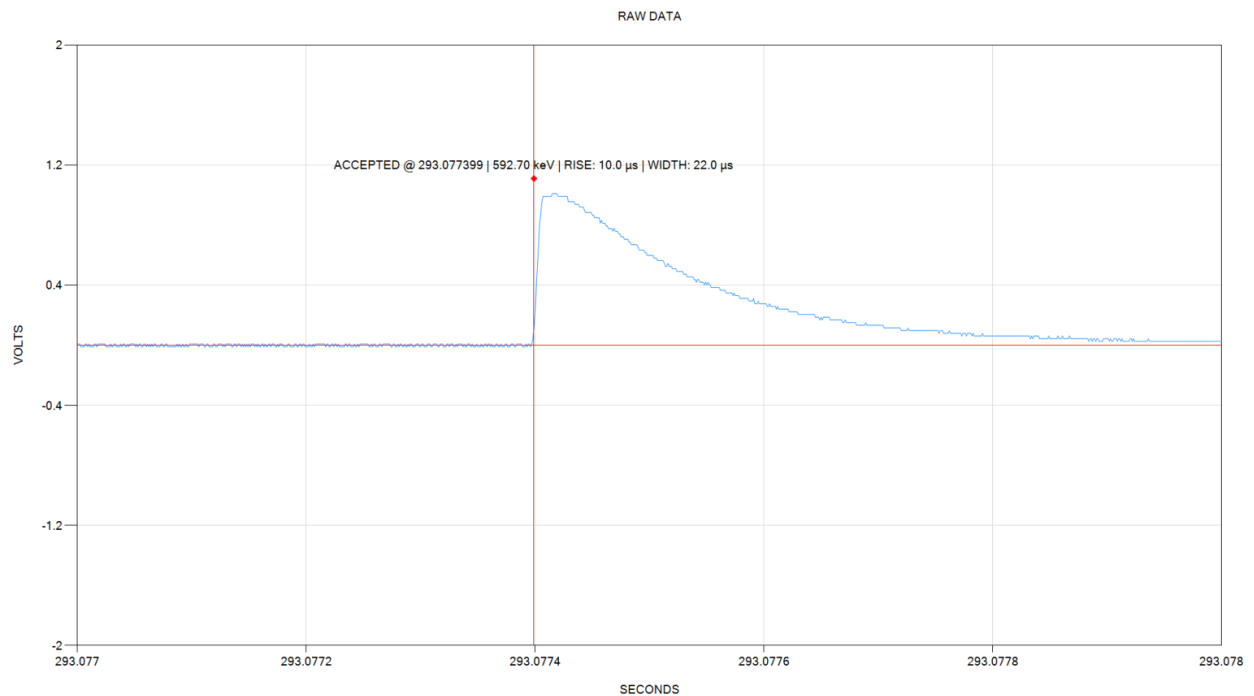


Fig. 1. Preamplified neutron pulse (voltage) from a ^3He proportional counter.

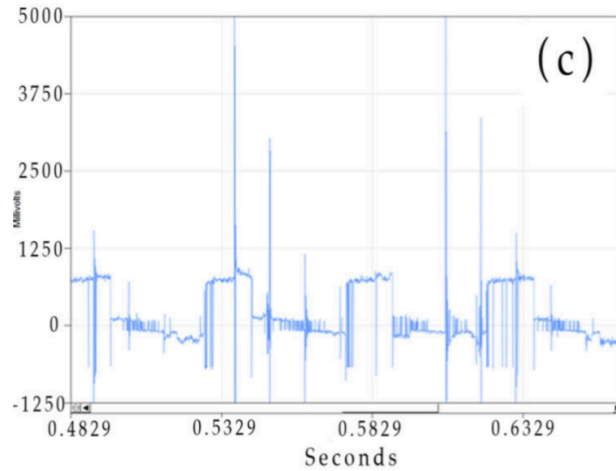


Fig. 2. Typical RF interference in the detector signal.

As such, for a critical experiment, it is necessary to capture the raw detector signal for manual inspection/validation.

Because eliminating RF interference can be time-consuming and high noise levels may render the detector signal unusable, it is desirable to have a detector architecture that is as insensitive to electromagnetic noise as possible.

4. NEUTRON-X Detector System

To address the RF interference problem, we introduce a novel neutron detector design, NEUTRON-X, characterized by balanced signalling (Fig. 3).

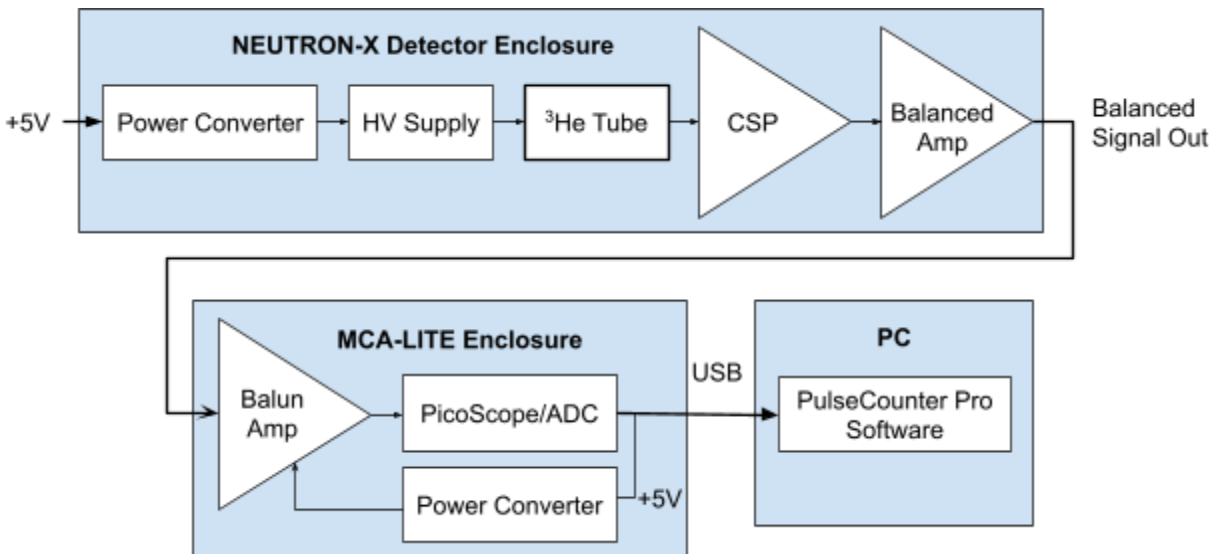


Fig. 3. NEUTRON-X block diagram.

The NEUTRON-X detector enclosure contains a proportional counter tube, a built-in HV bias supply, a charge-sensitive preamp, and a balanced amplifier. The detector communicates the balanced signal to the MCA via a standard USB Type-C cable of arbitrary length, allowing the detector to be as close to the neutron source as possible while keeping the MCA at a safe distance from the source. The MCA includes a balun amplifier that converts the balanced signal to a ground-referenced RF output, which can be digitized and processed on a standard MCA, such as an AmpTek DP5 or a Maximus Energy MCA-LITE/MCA-PRO²⁰ (Fig. 4).



Fig. 4. NEUTRON-X detector system.

Integrating the ^3He -filled proportional counter with the HV power supply, charge-sensitive preamp, and the balanced amplifier within an electrically sealed aluminum enclosure provides Faraday screening for the sensitive electronics, allowing only the unshielded USB-C cable used for the balanced detector signal communication to be affected by RF interference.

When the magnitude of electromagnetic noise is high, the DPP/MCA must be located sufficiently far from the source of the RF interference, where there is no risk that the ADC circuit will pick up enough noise to invalidate the analog-to-digital conversion.

In practice, the balanced signaling architecture effectively eliminates most common RF interference, including ground loops and RF voltage spikes caused by poor grounding, electric motors, high-voltage discharges, plasma sources, or variable-frequency drives, thereby producing a clean, interference-free detector signal.

5. Low-Cost Hardware Architecture

To make the NEUTRON-X detector system affordable, we leverage off-the-shelf components for digital pulse processing. Specifically, we employ Pico Technology PicoScope digital USB oscilloscopes for nuclear data acquisition due to their low cost and high signal acquisition quality. For example, an amplified, ground-referenced neutron detector signal can be sampled in real time using a PicoScope 2204A (Fig. 5).



Fig. 5. Low-cost neutron detection architecture.

PicoScope 2204A costs under \$150, supports continuous/streaming sampling rates up to 5 MHz, and features 8-bit resolution and 10 MHz bandwidth, which are more than sufficient for neutron signal processing. PicoSDK provides a convenient API for developing custom software for data acquisition and pulse processing. This is why we selected this hardware platform as the basis for PulseCounter Pro software¹⁹, which we include with each NEUTRON-X system.

For high-resolution gamma spectroscopy, ADC resolution better than 8 bits is desirable. Therefore, for gamma spectroscopy, we recommend the PicoScope 4224A, 4424A, and 4824A hardware, which are characterized by 12-bit resolution and 20 MHz bandwidth, yet cost just under \$1,000 for a 2-channel 4224A model.

The added benefit of using the PicoScope/PicoSDK architecture is the ability to run multiple detectors in parallel, with each detector feeding a signal to a separate PicoScope channel. This approach enables simultaneous, cost-effective data acquisition from up to 8 nuclear radiation detectors using a PicoScope 4824A.

6. Thermal Neutron Spectrum

While superb (in fact, the highest-known) sensitivity to thermal neutrons is the main reason why we advocate for the use of ^3He -filled proportional counters as opposed to liquid scintillators or other detector types, the second equally important reason is the easily recognizable shape of the thermal neutron spectrum that these detectors produce (Fig. 6).

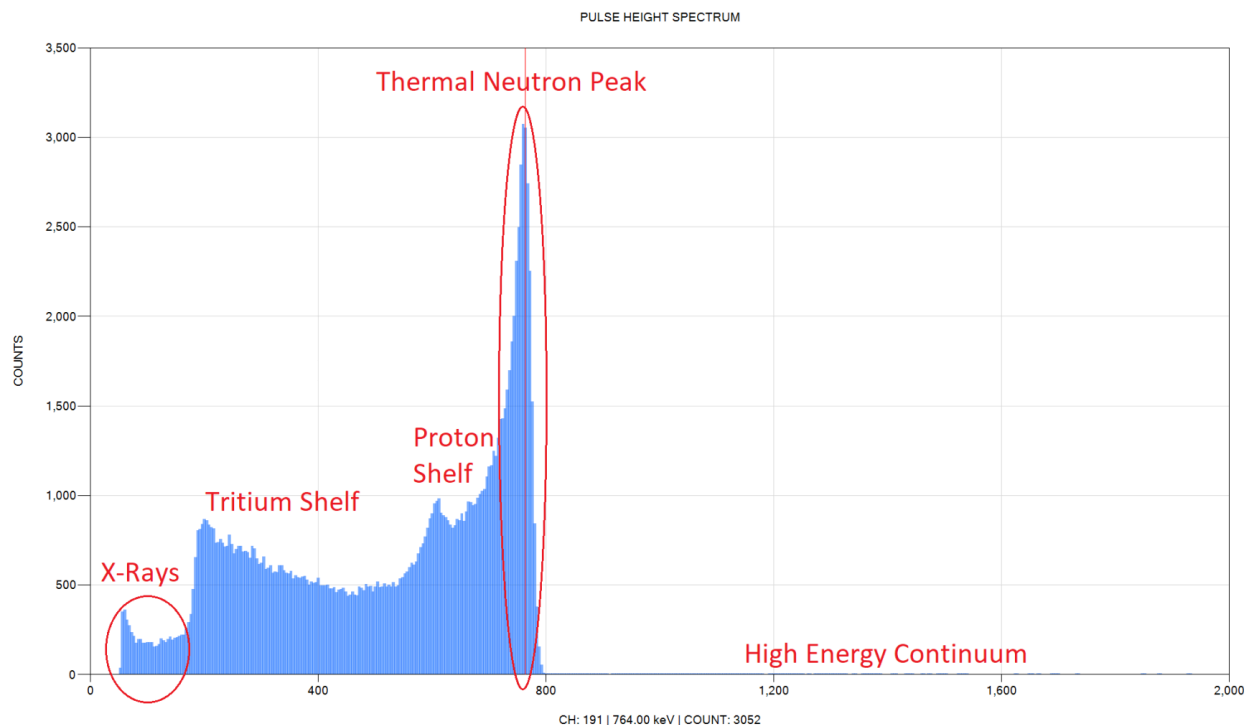


Fig. 6. Thermal neutron spectrum.

There is a common misconception that the thermal neutron spectrum is related to the energy of the detected neutrons; it is not. The thermal neutron spectrum has little to do with the energy of neutrons being counted and merely corresponds to the 'fingerprint' of a detector.

^3He proportional counters are best suited for detecting thermal neutrons, i.e., neutrons that have lost their high initial energy through scattering in the environment or moderator. The thermal neutron detection efficiency of a ^3He detector approaches 100%. While a ^3He proportional counter can also detect fast neutrons, the detection efficiency is 10,000 times lower, amounting to merely 0.1%¹². Therefore, for low count rates, we are always interested in maximizing the counts, which means that we must properly thermalize fast neutrons by enclosing the detector within 2-3" of high-density polyethylene (HDPE) moderator or another suitable moderation material, such as high-purity carbon. In the process, the information about the neutrons' initial energy is completely erased, yet the detection efficiency is maximized.

When a ^3He -filled proportional counter is operating correctly and the neutron flux is properly moderated, the detector will always produce a thermal neutron spectrum regardless of the original energy of neutrons emitted by the source. Thus, the shape of the thermal neutron

spectrum is a mere indicator of the underlying detector physics. When a ^3He nucleus captures a neutron, it decays into a triton and a proton. When these charged particles ionize the gas within the proportional counter, they give rise to current pulses of two distinct amplitudes corresponding to the proton and triton shelves, with the sum peak amounting to the most prominent feature of the thermal neutron spectrum (Fig. 6).

When neutron counts are low, we can ignore the neutron pile-up as well as the possibility of non-thermal neutron detection. As such, given enough neutron events (long enough counting time), a detector must produce a perfect thermal neutron spectrum. The observation/confirmation of a properly shaped thermal neutron spectrum is essential for reliable neutron detection. Visual inspection of the thermal neutron spectrum alone may be sufficient to determine whether the data are reliable, as deviations from the expected thermal neutron spectrum shape indicate RF interference or other problems in the data-acquisition electronics or digital pulse processing.

So, the proper thermal neutron spectrum shape is a 'litmus test' and an indicator of adequate neutron detection. Such a 'fingerprint' or 'litmus test' is not available for other detector types, such as crystalline or liquid scintillators, making them less suitable for *reliable* neutron detection.

7. Gamma and X-Ray Interference

We must remind the reader of the often-forgotten problem of gamma-ray and X-ray (or, in the most general sense, charged-particle) interference, which affects all known neutron detectors except, possibly, for bubble detectors²¹. Even though ^3He -filled proportional counters are usually marketed as 'insensitive' to gamma radiation, this statement is misleading and generally untrue. Proportional counters do react to gamma rays, producing current pulses with amplitudes usually lower than those of proper neutron pulses. As such, such pulses typically form an x-ray peak on the thermal neutron spectrum, which can be easily discriminated for by rejecting spectrum channels below 200 keV (Fig. 6).

However, the problem becomes more pronounced when the gamma radiation intensity increases markedly, for example, in the vicinity of an operating reactor¹². In this case, due to gamma-pulse pileup, the x-ray peak tends to shift to the right on the energy scale and encroach on the thermal neutron spectrum. This is another reason why the thermal neutron spectrum should be monitored at all times, as it is impossible to distinguish a genuine neutron pulse from multiply-piled gamma pulses that produce a pulse of equivalent strength.

In a situation like this, the x-ray peak will overlap the thermal neutron spectrum, requiring the rejection of more spectral channels to preserve the veracity of neutron counts, though at some loss of sensitivity. This is an unavoidable problem. When sensitivity reduction is not permissible, lead-based detector screening may be necessary to mitigate the impact of gamma counts on the thermal neutron spectrum.

8. Acoustic Interference

^3He -filled proportional counters are susceptible to acoustic interference, such as mechanical vibration, which may result in false peaks appearing in the detector signal. It is essential to insulate the detector from vibration sources to obtain a clean signal. Fortunately, monitoring the thermal neutron spectrum provides another indicator of possible acoustic interference, as it would distort the spectrum and thereby indicate the problem.

9. Screening and Moderation

Another common source of systematic errors in neutron detection is improper moderation, screening, or alteration of the experimental configuration between measurements. This is another area in which classical intuition fails. Indeed, when measuring voltages or currents, it is largely unimportant where we place our electric meters and where other instruments and personnel are located during measurement. The situation is radically different when measuring radiation in general and neutrons in particular. Under most circumstances, neutron radiation is isotropic in its spatial distribution. As such, moving equipment, changing detector location (e.g., even slightly), or allowing people to move about while conducting extended measurements may, and in all probability will, affect the count rates, as the geometry of the experimental setup is fundamental. Various pieces of equipment and people, too, serve as absorbers of neutron radiation. Human bodies, due to their high water content, also serve as moderators, slowing down fast neutrons. In the case of already thermalized neutrons, the human body is a good absorber: any hydrogen-rich material has a considerable thermal neutron absorption cross-section.

As such, no change in the neutron detector positioning or orientation, or movement of the experimental equipment or human participants can be permitted during neutron counting, as invariably such variability introduces noticeable change in counts during the experiment.

Because hydrogen absorbs thermal neutrons, deuterated moderators (such as heavy water) yield higher detection sensitivity. Unfortunately, deuterated materials are too expensive to be practical, with the possible exception of heavy water. That is why graphite moderators may be preferable for extremely weak signals since high-purity graphite has a low thermal neutron absorption cross-section compared to protium (^1H).

Typically, 2-3 inches of HDPE moderator are used around the detector. The optimal thickness depends on the neutron energy. A moderator that is too thin may result in a reduced sensitivity due to partial thermalization. In contrast, a moderator that is too thick may also result in diminished sensitivity due to neutron absorption. If necessary, a Los Alamos Monte Carlo N-Particle Transport Code (MCNP) can be used to accurately model neutron propagation given the exact geometry and neutron energy of the experiment²². Such modeling can help determine the optimal moderator thickness and placement under the most realistic conditions.

For maximum detection efficiency, it is best to place the neutron detector as close as possible to the neutron source and to surround both the detector and the source with a moderator (Fig. 7).

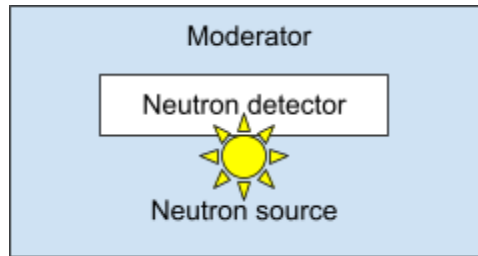


Fig. 7. The optimal neutron detector and moderator placement with respect to the neutron source.

10. Statistical Analysis

While X-rays, RF interference, screening, and acoustic noise are common sources of systematic errors in neutron counting, statistical analysis is another often-overlooked issue in radiation detection. Despite more than 100 years since the introduction of the quantum theory, quantum mechanics remains a confusing and counterintuitive subject for many physicists, including nuclear science experimentalists, who, to this day, think of their experiments, particles, and detectors in classical terms.

The inherent danger of such thinking is the neglect of statistics, which seems superfluous in most applications of classical mechanics. Radiation detection, however, falls firmly into the quantum-mechanical realm, and the only proper way to approach it is to abandon our classical intuition and always think in quantum-mechanical terms.

The most straightforward approach is to treat each radiation detector as a random number generator. Such a parallel is by no means a pedagogical approach but a mere statement of fact. Taking a singular reading from a radiation detector is utterly meaningless, as it is strictly equivalent to rolling a dice: the detector can produce any number of counts when we sample its readings. This happens because nuclear processes that produce the radiation that we measure are probabilistic in nature and are typically described by normal distributions. When we take a reading from a detector, we effectively sample from a normal distribution, and there is no way to tell whether the sample corresponds to the mean or lies a few standard deviations away from it. Only by collecting a sufficient number of readings can we sample the shape of the normal distribution well enough to estimate its mean and the standard deviation with accuracy. This is a common statistical problem that was addressed and solved long ago. Yet a casual survey of the nuclear science literature reveals systematic neglect or misuse of statistical analysis.

Granted, statistical analysis may appear superfluous when the counts are high, and the resulting normal distributions are razor-sharp. This is the boundary at which quantum mechanics transitions to classical behavior; our intuition is once again correct; however, statistical analysis remains necessary to demonstrate this.

Nevertheless, when measuring exceedingly small signals – meaning the signals on par with the background – we must never neglect the statistical analysis and collect enough detector

readings to safely reconstruct the normal distribution we are sampling and estimate the mean and variance with a sufficient degree of confidence.

10.1 Comparative Analysis

Proper use of statistics reminds us that all analysis is comparative. That is, neutron counts, even if properly sampled, are meaningless by themselves, as we always must compare them to the background (control). Indeed, how do we know if we have an excess count of neutrons when we do not have a baseline to compare against?

Here, we encounter another common mistake. Even experienced experimentalists overlook that the natural background (or any other form of control used for comparison) is also a random number generator subject to random fluctuations. In fact, this is where our intuition regarding the behavior of random processes fails us completely, as we have a misconception that a sequence of zeros and ones, such as 101010101, is random. In contrast, a sequence such as 1111110000000 is not. Subconsciously, we confuse uniformity with randomness, when in fact the reverse is true: uniformity is precisely the lack of randomness, whereas weird flukes and spikes, and prolonged periods of lull, characterize true randomness.

Put in a statistical context, an insufficiently long counting time may yield data that looks strange or is mistakenly interpreted as a 'meaningful' or even 'miraculous' event when, in reality, the detector yielded the random counts that still fit the normal distribution we are sampling. The literature is replete with such reports of 'strange' emissions that cannot be repeated. This is a definition of randomness! The confusion is easily remedied by increasing the sampling time and by statistically comparing the experimental counts with the background. Repeatability is also key. Any result, no matter how weird, means absolutely nothing if it cannot be repeated. Such is the (confusing!) nature of randomness.

10.2. Poisson Distribution

When measuring signals from nuclear processes, we are primarily interested in the count rates. A count rate is the number of detected events per unit time. When we count normally-distributed random events and bin them into discrete time intervals, we obtain a Poisson distribution, which may look very different from the normal distribution at low count rates but asymptotically approaches it at high count rates. In fact, at high count rates, the Poisson distribution becomes indistinguishable from the normal distribution, where the distribution mean equals the distribution variance (Fig. 8).

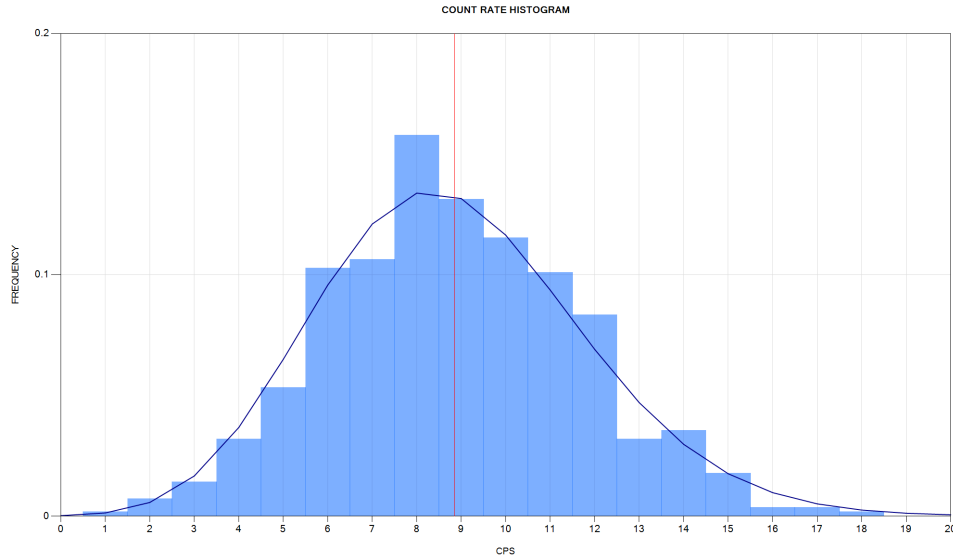


Fig. 8. Count rate histogram fitted to a Poisson distribution.

We can use statistical tests (e.g., the chi-square test) on our count-rate samples to assess the goodness of fit to a Poisson distribution. If the quality of fit is poor, then the distribution is non-Poisson, which can mean one of two things:

- The process we are observing is non-random, or
- The count rates were affected by systematic errors or noise.

Thus, by monitoring the count-rate distribution, we can detect deviations from the expected randomness, which are indicative of non-random processes.

The non-random nature of the process could result from the operator's interaction with the experimental setup or measurement instrument, or from systematic errors associated with detector malfunction, faulty cabling, electromagnetic interference, positioning errors, and similar sources.

At other times, the non-random nature of the process indicates control: for example, by shutting down the reactor, we ought to reduce the counts. By definition, control is the opposite of randomness. This is why demonstration of control is essential for many experiments.

In any case, by examining the shape of the count rate histogram, one can derive practical conclusions about the random vs. non-random nature of the observed process.

10.3 Student's T-Test and P-Value

Once a set of the 'background' and the 'experiment' measurements is acquired and the corresponding population means and standard deviations are calculated, one can start looking for differences between the 'experiment' and the 'background' count rates. A mere presence of the difference in the mean count rates between the two populations, however large, is not an indication of the actual difference. Instead, a statistical analysis must be conducted to determine

if the two population means are in fact different (as opposed to merely appearing different due to insufficient sampling).

One such standard tool for comparing populations is Student's t-test. This test yields a numerical measure, the p-value, that can be used to assess the statistical significance of the results. For example, if the background and the experiment counts are evaluated using Student's t-test and the resulting p-value is greater than 0.05, the results are considered not *statistically significant*, meaning that the observed difference between the 'experiment' and the 'background' count rates is not likely to be genuine. This means that the two count rates are essentially the same, and the observed numerical difference in the count rates (however large) must be due to the insufficient sampling.

At the same time, a p-value less than or equal to 0.05 indicates *statistically significant* results, meaning that the observed difference between the 'experiment' and the 'background' count rates (however small) is likely to be genuine.

10.4 Power of Test

When the number of acquired samples is small, the veracity of Student's t-test can be questioned. To provide additional assurance, the test's power should be evaluated. For example, Lehr's rule of thumb is often used to determine if a Student's t-test calculation was made using enough samples to be trustworthy.

10.5 P-Value Trend

Acquiring additional 'background' and 'experiment' measurements may result in a p-value trend. If the p-value is increasing with each additional measurement (p approaches 1), this means that there is no difference between the 'experiment' and the 'background' count rates, and any initial indication of significance ($p \leq 0.05$) was likely in error.

Conversely, if the p-value is decreasing with each additional measurement (p approaches 0), this means that there is a genuine difference between the 'experiment' and the 'background' count rates, and the initial indication of poor significance ($p > 0.05$) was likely in error.

In other words, any results that are being presented as 'statistically significant' must improve in significance ($p \rightarrow 0$) with the increase in the number of measurements. This is a must-have sanity check for presenting high-veracity results. Without the p-value trend, one can still be fooled by randomness.

11. Background Counts

The 'background' counts pertain to sampling of random processes associated with a complex and variable natural environment. Proper background measurements must be meticulous, yet they are often overlooked, or the background is incorrectly presumed to be invariable. Specifically, it is easy to be fooled by randomness and dismiss unexpectedly large background

counts as erroneous, as they defy our classical intuition. But this is precisely what randomness is! Random numbers are expected to be surprising, and their sequences are not intuitive. In other words, when one turns on a detector to measure the background, the detector can and will occasionally report unexpectedly high or unexpectedly low count rates that will utterly defy our expectations; this is normal. The longer one samples the background, the larger extremities one will observe. But in the end, the count rate histogram of any background measurement must follow a Poisson distribution regardless of how large, small, or peculiar the individual count rate samples are.

Therefore, a singular extreme reading reported by a nuclear detector should not be interpreted as evidence of something unusual or discarded as 'erroneous'; it is likely to be a manifestation of quantum randomness. It is also never correct to assume that the background is 'stable' or invariable. Stability, predictability, and periodicity are the opposite of randomness. We should see none of that when we measure the background.

Cosmic rays primarily contribute to the natural neutron background and therefore exhibit considerable variability. Such variability is expected and should not be surprising. The cosmic neutron flux can be augmented by weather-related neutron flux; thunderstorms and lightning are known to generate neutrons²³. Regardless, the shape of the background neutron spectrum reported by a ^3He -filled proportional counter must always match the thermal neutron spectrum.

Natural neutron background can be reduced by surrounding the detector and the experimental setup with a 'castle' containing neutron-absorbing elements such as hydrogen, boron, or cadmium. In practice, cadmium foils, boric acid, Borax, HDPE, water, and mineral oil are commonly used to shield detectors from the environmental neutrons. Experiments staged below ground will also benefit from the reduced neutron background.

12. Increasing Signal to Noise: Background Reduction

Because in the course of a nuclear physics experiment, we are constantly comparing the 'background' and the 'experiment' measurements, it is desirable to reduce the background counts. This is usually accomplished in two ways:

- Lead shielding is commonly used to screen the background gammas, whereas high-density polyethylene (HDPE) or boron-rich shielding is typically used to screen the background neutrons.
- Some experiments are conducted deep underground, where the Earth itself screens out much of cosmic radiation, including neutrons and high-energy muons.

Regardless, background count reduction is an important activity that helps increase the signal-to-noise ratio when comparing the 'experiment' and the 'background' measurements. Additionally, background reduction is a vital sanity check: the statistical significance of the results must improve when the experiment is repeated under reduced background conditions. If this does not occur, the observed apparent difference in count rates is not genuine.

13. Detector Calibration and Check Sources

Nuclear instruments require regular calibration. In fact, most instruments should be calibrated (or at least calibration-checked) before each experiment.

Because most detectors report counts that depend on the physical size of the detector element, its intrinsic sensitivity, and orientation, it may be necessary to run a sensitivity calibration to establish a relationship between the reported count rate and the actual particle flux (e.g., convert neutron counts to neutron flux per cm^2). Calibration of neutron detectors requires neutron sources that, in the U.S., generally require an NRC license. Common sources are Po-Be, Pu-Be, Ra-Be, or Cf. Such sources are characterized by a known NIST-certified activity of a few curies. They can be used to calibrate the sensitivity of a neutron detector and, when appropriate, its energy resolution.

Neutron detectors are typically calibrated using NIST-traceable neutron sources such as Pu-Be, Ra-Be, Am-Be, or Cf-sources. A few curies of activity usually characterize such sources and therefore require an NRC license for purchase and operation.

While a NIST-traceable source is necessary to establish the detector sensitivity precisely, any neutron source will suffice to verify the shape and calibrate the energy of the thermal neutron spectrum. In fact, even without a source, it is possible to calibrate a thermal neutron spectrum simply by counting background neutrons for several days. With a typical background count rate on the order of 1-5 CPM, it will take 1-4 days to acquire enough data points to resolve the shape of a thermal neutron spectrum.

Clearly, waiting for a few days is impractical; it is beneficial to build a neutron check source as follows: in the United States, a commercial 5 mCi ^{210}Po alpha-source can be purchased from AmStat Industries under a compulsory NRC license²⁴; such a source can be paired with a beryllium window to form a neutron check source (Fig. 10).



Fig. 10. Po-Be neutron check source: a Nuclespot P2042-1000 static eliminator is paired with a circular thin beryllium window covered with a brown cardboard plug.

When alpha particles emitted by ^{210}Po strike beryllium, some of them are absorbed by beryllium nuclei, emitting neutrons in the process. While the beryllium window thickness does not play a significant role, placing the window as close to the ^{210}Po bulk as possible makes a huge difference: alpha particles do not travel very far in air, and most of them lose all of their energy after crossing an air gap of just a few millimeters. Therefore, the resulting neutron flux will be highest when the beryllium window is placed flush with the ^{210}Po -containing material.

Also, keep in mind that such a check source is not directional, and it emits neutrons uniformly over the 4π solid angle.

14. Common Sources of Systematic Errors

To recap, when working with a ^3He -filled proportional counter, some common sources of systematic errors are as follows:

- **Ground loops:** Due to the small magnitude of the detector signal (a few mV), noise from switching power supplies is often the primary source of EM interference; high-quality grounding and loop-elimination techniques must be used to reduce this noise. This problem is largely eliminated in the NEUTRON-X system.
- **Electromagnetic coupling:** the smallness of the magnitude of the detector signal makes a detector susceptible to the EM interference due to capacitive or inductive coupling; this coupling can be eliminated by screening the detector with a grounded copper shield or by enclosing the entire detection system in a Faraday enclosure; this problem is also largely eliminated in the NEUTRON-X system.
- **Vibration:** electrical contacts within the detector (e.g., the anode mounting) may be affected by mechanical vibration, resulting in artificial pulses due to microphonics or the intermittent loss of contact. Acoustic foam should be used to insulate proportional counters from mechanical contact with vibrating equipment.
- **Temperature variations:** ^3He proportional counters are generally insensitive to temperature variations; however, depending on the detector's age, mechanical contacts may be disrupted by non-uniform thermal expansion, resulting in spurious pulses.
- **Changes in detector position and orientation** are a common source of count-rate variability: even slight movement of the detector relative to the source, or slight displacement of the source relative to the detector, will result in statistically significant changes in count rates when the measurement time is substantial.
- **Rearrangement of components or personnel movement** in the vicinity of the measurement setup may also result in systematic errors in count rates due to background screening and/or unintended moderation (the human body is mostly water, and water is an excellent moderator).

Fortunately, artificial pulses arising from systematic errors can be detected by examining the raw detector signal and verifying the thermal neutron spectrum shape. Any deviations from the expected pulse shape or from the expected appearance of the thermal neutron spectrum are signs of interference.

15. General Protocol for High-Veracity Measurements

Summarizing the discussion above, we propose the following protocol for high-veracity measurements:

1. Properly shield instruments from common sources of acoustic or electromagnetic interference.
2. Calibrate detectors.
3. Acquire a large sample of the 'background' count rates.
4. Acquire a large sample of the 'experiment' count rates.
5. Perform Student's t-test on the 'background' and the 'experiment' count rate populations, and calculate the p-value.
6. If the p-value is 0.05 or less, the difference in the count rates is statistically significant.
7. To gain further certainty, do the following:
 - a. Evaluate the power of the test (e.g., Lehr's rule) to make sure that enough samples were used to calculate the p-value.
 - b. Examine the pulse-height spectrum: does it match the expected shape?
 - c. Examine the count rate histogram: does it follow a Poisson distribution?
 - d. Compare the rise time and the pulse width histograms of the 'background' and the 'experiment' measurements: do they match?
 - e. Examine the raw detector signal: does it appear free from noise? Are the counted pulses characterized by the expected rise time, pulse width, and decay time?
 - f. Make additional measurements and derive a p-value trend: does the p-value tend to decrease ($p \rightarrow 0$) with the additional measurements?

Thus, when $p \leq 0.05$ and the conditions 7a through 7e are satisfied, we can claim that the difference between the 'experiment' and the 'background' count rates is established beyond a reasonable doubt.

Following these steps is a tedious but necessary process. To help researchers meet these rigorous requirements, we have developed the PulseCounter Pro software²⁰, which automates this process and enables the derivation of real-time conclusions regarding the significance of results.

16. Case Study

The following example illustrates a neutron detection process implemented in accordance with the best practices outlined in this paper. The hardware was an MCA-PRO connected to an assembly of six LND 251106 detectors arranged in a bank (Fig. 11).

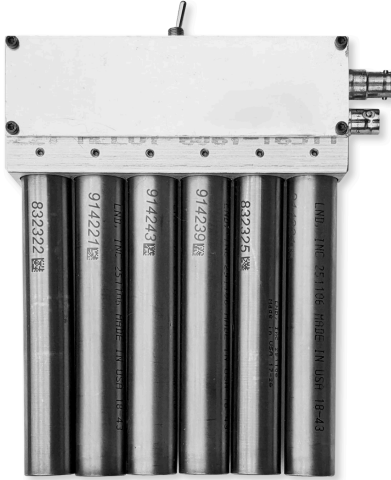


Fig. 11. The bank of six LND 251106 ^3He proportional counters with a built-in 9V battery-powered preamp.

The detector bank was fitted with a built-in 9V battery-powered preamplifier to amplify the detector signal and output short ($\sim 10 \mu\text{s}$ duration) positive-polarity pulses with amplitudes between 1 and 100 mV. The detector bias was set to 1,050 V, and the detector signal was acquired at a 1 MHz sampling rate using MCA-PRO. PulseCounter Pro was used to shape the detector pulses digitally via trapezoidal filtering. All shaped pulses with an amplitude below 3 mV were rejected eliminate the gamma peak.

To reduce the background, we have enclosed the detector and the experimental setup in a Borax castle (Fig. 12).



Fig. 12. Borax castle around the neutron detector and the experimental setup.

The resulting reduction in the background counts was 10x, with the mean background count rate being 6.4 CPM.

During the course of the experiment, we have captured 116 ‘background’ and 42 ‘experiment’ measurements, each one minute long (Fig. 13).

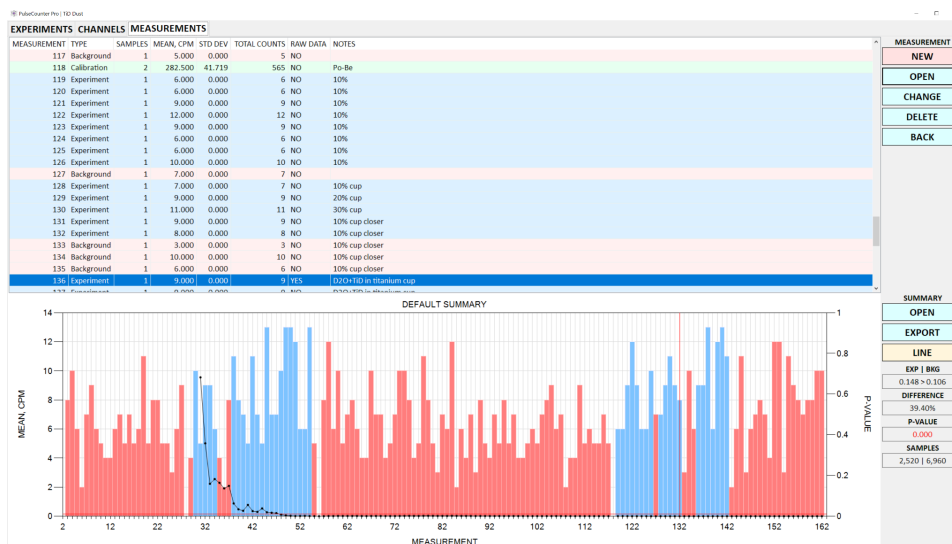


Fig. 13. The summary plot of the ‘background’ (red) and the ‘experiment’ (blue) mean count rates; the black line gives the p-value trend.

As one can see from Fig. 13, the results of statistical analysis of the captured measurements support the hypothesis that the ‘experiment’ mean count rate exceeds the ‘background’ mean count rate by ~40% (8.9 CPM vs 6.4 CPM, $p < 0.001$). We also observed a declining p-value trend as we increased the number of measurements, which further corroborated the hypothesis that the ‘experiment’ mean count rate is indeed different from the ‘background’ mean count rate.

To validate this conclusion, we have merged all the ‘experiment’ and all the ‘background’ measurements into two datasets and compared the resulting neutron spectra - Fig. 14.

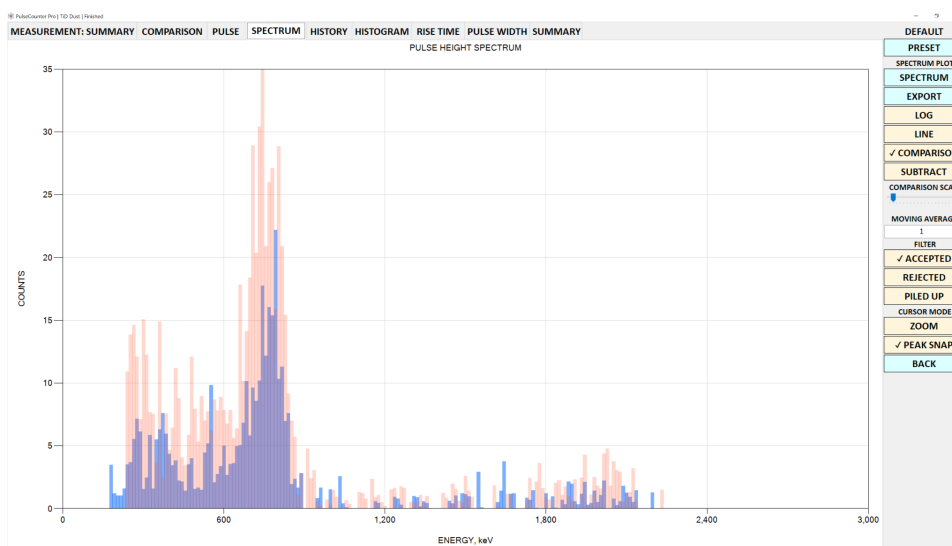


Fig. 14. The spectra of the merged ‘experiment’ and ‘background’ measurements.

The resulting spectra match the thermal neutron spectrum for the detector bank, which was obtained separately using a Po-Be check source. Fig. 14 does not show any unusual peaks or any significant deviations from the expected shape of the thermal neutron spectrum.

To further validate the conclusion, we examined the count-rate histograms and found them to fit the Poisson distribution well (χ^2 test, $p = 0.748$; Fig. 15).

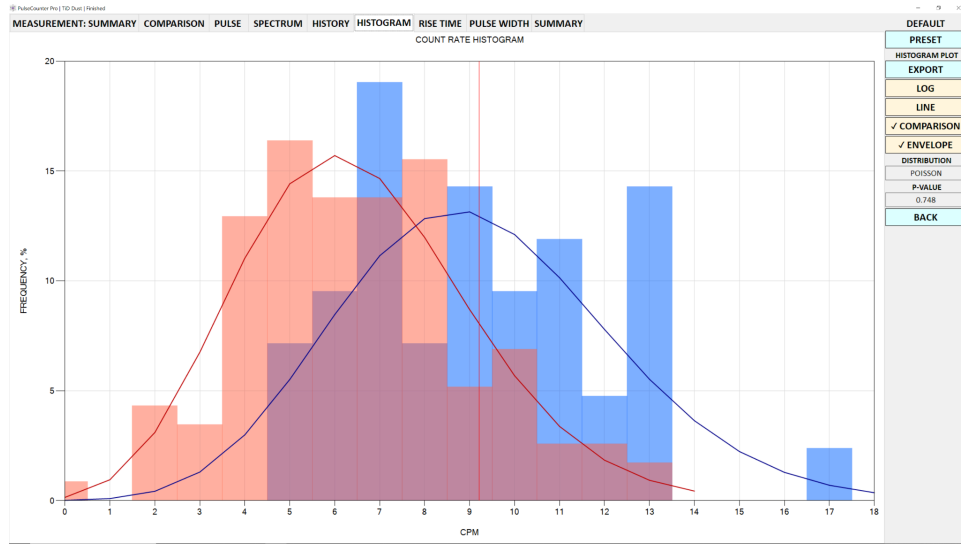


Fig. 15. The count rate histograms of the merged ‘experiment’ and ‘background’ measurements with the corresponding Poisson distribution envelopes.

Also, we did not observe any significant differences in the rise time and the pulse width histograms between the ‘experiment’ and the background measurements - Fig. 16.

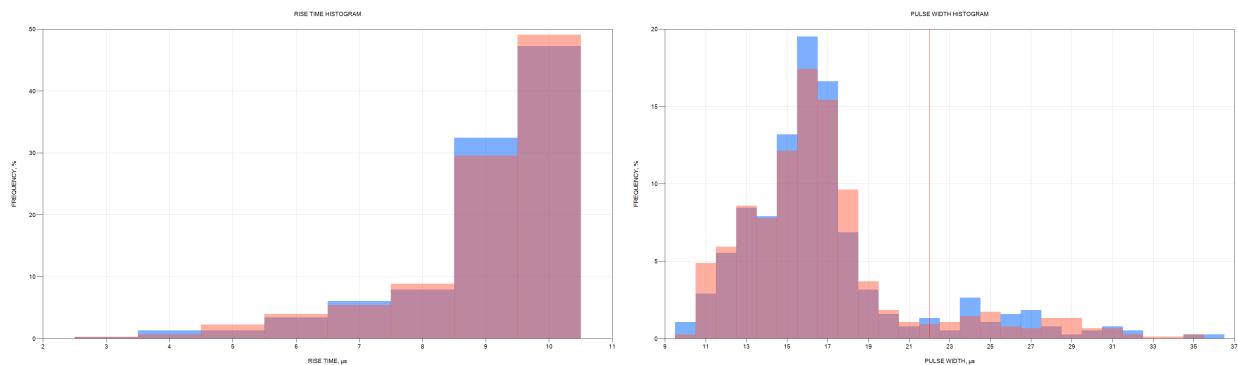


Fig. 16. The rise time (left) and the pulse width (right) histograms of the ‘experiment’ (blue) and the ‘background’ (red) measurements.

Lastly, we examined all counted pulses by browsing the recorded raw detector signal and did not detect any abnormalities (Fig. 17).

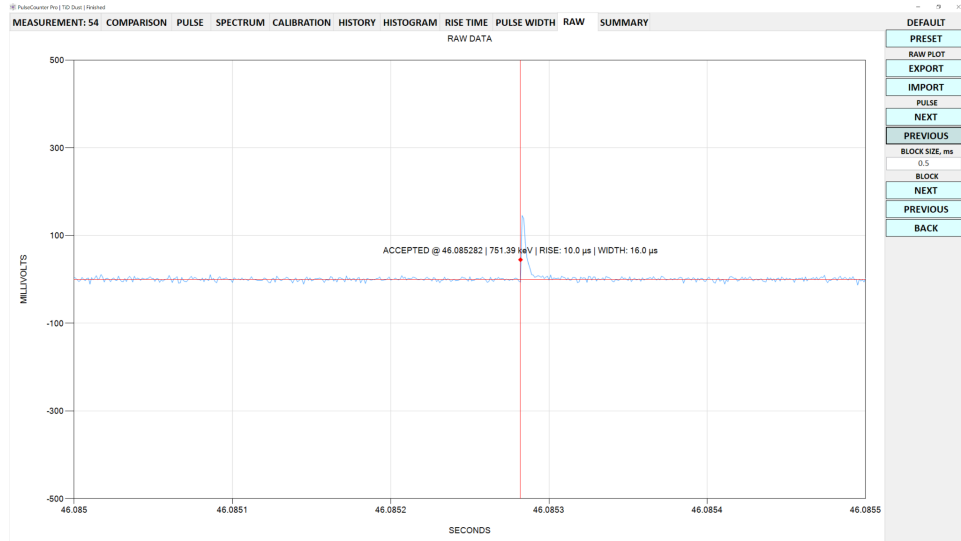


Fig. 17. Raw detector signal illustrating a single counted neutron pulse.

Taken together, all the presented evidence strongly supports the hypothesis that the observed 40% increase in the mean count rate associated with the ‘experiment’ is genuine and highly statistically significant ($p < 0.001$). In fact, in light of the comprehensive nature of the performed validation steps, it is safe to conclude that the increase in neutron counts is established beyond a reasonable doubt.

Conclusion

In this paper, we have examined issues in radiation detection and discussed common sources of systematic errors that affect the reliability of neutron counts. We have introduced the NEUTRON-X detector system, which is virtually impervious to RF interference, and outlined a protocol for reliable neutron detection using ^3He -filled proportional counters. We intend this protocol to be used as a ‘gold standard’ for reliable detection of small neutron counts. We further introduced MCA-PRO and PulseCounter Pro hardware/software system as an affordable and versatile platform for radiation detection, which automates all tasks associated with the presented protocol for *reliable* neutron and gamma detection.

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Data Availability

There is no data available from this study.

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