Reliable Neutron and Gamma Detection

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Abstract

Ionizing radiation is a telltale sign of nuclear reactions. New physics aside, fusion, fission, radioactive decay, transmutation, nucleosynthesis and other types of nuclear reactions are universally expected to produce some form of radiation that can be observed and measured. However, measuring low levels of radiation (i.e. when the count rates are barely above the background) is anything but simple. In this paper we address this problem by presenting a robust radiation detection methodology developed specifically for measurements characterized by very low count rates or very minute count rate changes. We apply the developed methodology to two specific examples: neutron detection using ^{3}He proportional counters and gamma detection using NaI(Tl) scintillation detectors. We show that the developed methodology allows reliably establishing statistical significance of results when the count rates are on the order of a few CPM and when the difference between the 'experiment' and the 'background' count rates is very small. We also discuss systematic errors, sources of noise and show how the presented methodology can be used to address the common problems. The desired outcome of this paper is an educational one: we hope to teach the community the proper radiation detection technique and thus help experimentalists increase the quality of their data.

1. Introduction

Most radiation detectors produce current or voltage pulses corresponding to the detected nuclear particles. Detectors that produce current pulses usually employ charge-sensitive preamplifiers integrating the currents and converting them into voltages [1]. In the end every detector produces a signal, which contains a series of pulses. This signal needs to be shaped and processed, and the pulses must be counted and analyzed in order to yield a count rate history and, when appropriate, a pulse height spectrum [2]. These are only a few tasks that comprise a 'measurement'.

Measurement in the general sense of the word is the most difficult part of any experiment. Measurements involving nuclear instruments are particularly difficult for the following reasons:

- Nuclear instruments are complex devices that require detailed understanding of the their operating principles and related physics;
- The analog signals produced by the nuclear detectors are usually very small: voltages on the order of millivolts, total deposited charges on the order of a few picocoulombs;
- Such small signals are easily corrupted by electromagnetic, environmental, or mechanical noise;

- More often than not we are looking for very small changes in count rates; such small changes require rigorous statistical analysis in order to be established with any meaningful certainty;
- Nuclear processes are governed by the rules of quantum mechanics; these processes are fundamentally random in nature and therefore defy our ‘classical’ intuition; understanding these processes requires solid knowledge of probability theory and statistics.

2. Random Processes

There is a big principal difference between the measurements of ordinary physical quantities such as temperature, weight or length and the measurements of count rates or activity reported by nuclear instruments.

For example, when we measure length we obtain a value whose accuracy is limited by the stated accuracy of the instrument. If we use a common ruler graduated in millimeters the typical accuracy is 0.5 mm. Additionally the measured length may be impacted by systematic errors pertaining to the use of the measurement device such as errors in the ruler positioning, curvature of the object being measured, etc. Yet even a single measurement typically yields a value representative of the true length with uncertainties that are usually very small compared to the value being measured. For instance, if we measure length with a ruler we may find it to be 100 mm ± 1 mm. Therefore in the classical realm a single measurement is generally representative of the value being measured and multiple measurements are necessary only if we wish to further reduce the already small measurement uncertainty. This intuitive approach to ‘classical’ measurements is based on our everyday experience with classical physics.

However, the situation is completely different when nuclear instruments are involved because these instruments operate according to the laws of quantum mechanics and therefore produce measurements pertaining to *random processes*. Randomness and random processes form the foundation of quantum physics, which can be understood only in terms of probabilities.

This means that a single measurement in the quantum realm is utterly meaningless because the value it yields is by definition random. Because this value is drawn from a random distribution (in most cases Normal distribution) it can range from zero to infinity. This situation is very different from measuring length with a ruler, where one always gets a certain value close to the true length. When measuring ‘quantum length’ with a ‘quantum ruler’ one can get values such as 0, 22, 311, 65000, etc. This is where our ‘common sense’ intuition stops being helpful and we must follow the rules of quantum mechanics and apply appropriate statistical techniques to interpret the results.

In other words, if one wishes to determine a neutron or gamma flux associated with a particular nuclear process and takes a single measurement, one gets a meaningless random value that cannot be interpreted in any useful way. To properly measure a neutron or gamma flux one must conduct a series of measurements to sample the distribution and subject the results to a statistical analysis. We can make sense of randomness only by way of statistics. Therefore, any measurement involving nuclear detectors amounts to acquiring multiple count rate samples over an extended period of time until we have a sufficiently large sample representative of the random distribution we are trying to sample.

As such, in the context of this paper conducting a *measurement* means acquiring a sufficiently large population of count rate samples, including estimation of the population mean and the standard deviation. Here the word 'estimate' (although synonymous with the word 'calculate') means that even though we are calculating the mean and the standard deviation we are only estimating their values, and the actual (true) values may be very different from the calculated ones due to the insufficient sampling. Such as the nature of randomness! Therefore we must conduct repeated measurements in order to ensure that our estimates converge on the true values and perform rigorous statistical analysis in order to make sense of the results.

3. Poisson Distribution

It is well established that nuclear physics is governed by the laws of quantum mechanics, which state that all nuclear processes involving radioactive decay, gamma emission, absorption, etc. are *normal processes* that follow Gaussian distribution of probabilities.

When we measure signals produced by nuclear processes (such as voltage or current pulses resulting from alpha or beta particles, neutrons, x-rays or gamma quanta interacting with the detector) we are primarily interested in the count rates. A count rate is a number of detected events per unit time. When we count random events and bin them into discrete time intervals we obtain a Poisson distribution, which may look very different from Normal distribution at low count rates but asymptotically approaches Normal distribution at high count rates. In fact, at high count rates Poisson distribution becomes indistinguishable from Normal distribution where the distribution mean equals the distribution variance. Fig.1 illustrates a count rate histogram fitted to a Poisson distribution.

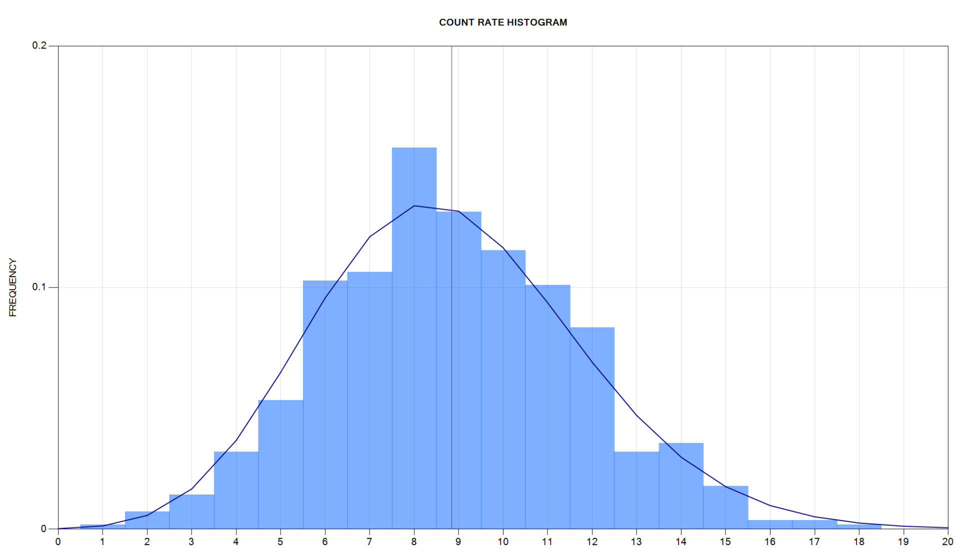

Fig. 1. Count rate histogram fitted to a Poisson distribution.

We can use statistical tools (such as χ^2 test) against the population of our count rate samples to see how well it fits a Poisson distribution. If the quality of fit is poor then the distribution is non-Poisson, which can mean one of the two things:

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

The non-random nature of the process could be the result of operator's interaction with the experimental setup or with the measurement instrument, or could be caused by systematic errors pertaining to a detector malfunction, faulty cabling, electromagnetic interference, errors in positioning, etc.

At other times the non-random nature of the process could be an indication of control: e.g. by shutting down the reactor we ought to be able 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 useful conclusions pertaining to the random vs. non-random nature of the observed process.

4. Background Counts

A unique feature of nuclear measurements is their relativity. Once again, consider the measurement of length with a ruler. This measurement is absolute in the sense that unless we take the ruler and place it against an object, the ruler does not report any measurements. The ruler only produces a measurement when we use it to measure the object. Therefore we deem such measurement an absolute.

The situation is totally different with nuclear detectors. As soon as one turns on a nuclear instrument, the instrument will begin reporting counts. In other words, the ‘quantum ruler’ starts measuring as soon as one touches it. The reason this happens is because we are always surrounded by the ‘sea’ of background radiation, some of which originates from outer space (cosmic rays, galactic supernova explosions, solar radiation, magnetosphere events, etc) and some of it originates on Earth due to the natural radioactivity of rocks and materials that surround us (granite, radon), human activities, and even weather (electric storms and lightning discharges are known to generate gamma rays, neutrons and even positrons). Hence all nuclear measurements are relative in nature and require two sample populations to be acquired and compared against one another: the ‘background' and the ‘experiment’.

The ‘background’ measurements 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 exactly what randomness is! Random numbers are supposed to be surprising and are not supposed to make any sense. 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 is the opposite of randomness. We should see none of that when we measure the background.

5. Background Reduction

Because in the course of a nuclear physics experiment we are always 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 commonly used to screen the background neutrons;
- Some experiments are conducted deep underground where the earth itself screens a lot of cosmic radiation, including neutrons and high-energy muons.

Keep in mind that when using lead shields additional problems may arise such as x-ray fluorescence (XRF) peaks from lead or other elements present in the shield. These peaks manifest themselves when the elements of the shield absorb and re-emit x-rays creating a characteristic invisible glow that registers as a distinctive sequence of peaks on the captured x-ray or gamma spectra. Therefore a lead shield may not always be appropriate; the XRF peaks originating from the shield will be significant when the gamma flux is high and therefore must be accounted for.

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

6. Detector Calibration

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). Alpha, beta and gamma sensitivity calibration can be accomplished by way of exempt sources available from Spectrum Techniques.

Additionally, such sources can be used for energy calibration of the pulse-height spectra to establish the relationship between the magnitude of the detector pulses and the corresponding particle energy. The most commonly used gamma sources are:

- ^{57}Fe for calibrating x-ray detectors using the 5.9 keV line;
- ^{137}Cs for calibrating medium energy gamma detectors using the 661.7 keV line, and
- ^{60}Co for calibrating higher energy gamma detectors using the 1.17 and 1.33 MeV lines.

Gamma detectors in general and scintillation detectors in particular require frequent energy calibration due to energy resolution dependency on temperature. Spectral peaks do shift with the ambient temperature changes thus potentially affecting the counts.

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 on the order of a few curies and therefore can be used to calibrate sensitivity of a neutron detector and, when appropriate, its energy resolution.

7. Noise

Every electronic device has intrinsic electronic noise. In the case of nuclear instruments this intrinsic noise can be confused for genuine signal corresponding to particles being counted because detectors output pulses of varying amplitude and some of these pulses can have a very low amplitude. Thus, virtually all nuclear instruments require a choice of a low level discriminator *threshold* to draw a virtual line below which the pulses are considered noise and therefore should be ignored while above which the pulses are considered genuine and therefore should be counted - Fig. 2.

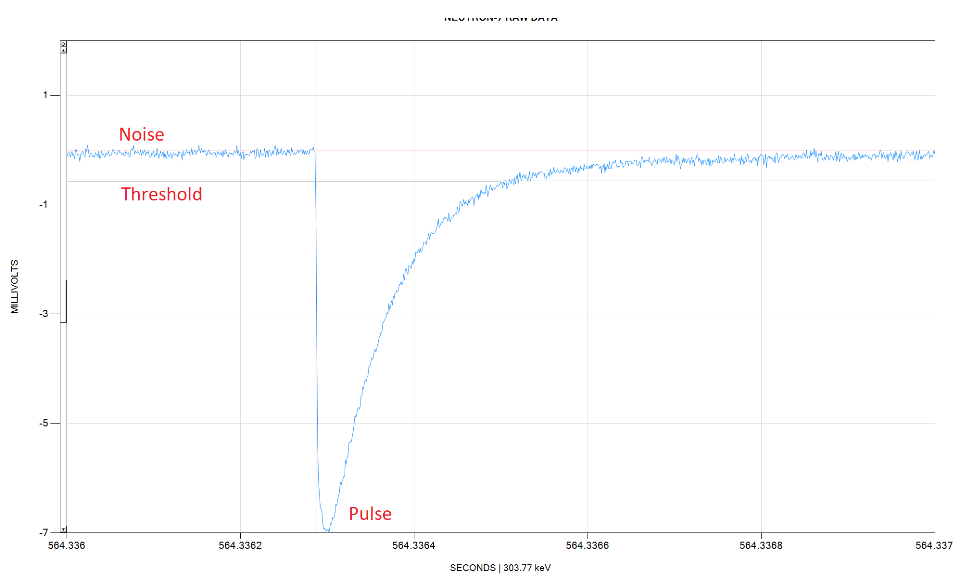

Fig. 2. A detector signal illustrating a genuine pulse, intrinsic noise, and the pulse discrimination threshold.

Ideally the threshold should be set just above the level of noise.

Besides the intrinsic noise there are other sources of interference that may introduce significant levels of noise into the measurement systems. Some possible sources of noise are:

- Electromagnetic waves / RF interference from switching power supplies, plasma discharges, spark gaps, etc;
- Capacitive or inductive coupling;
- Ground loops;
- Mechanical noise due to intermittent contact and microphonic effects.

In general no nuclear instrument is immune to noise. In fact nuclear instruments are often very sensitive to noise because of the small magnitude of pulses most detectors produce. This noise can be a huge nuisance during an experiment because it is often random in nature and therefore may masquerade as a random process.

In some cases the noise is a side-effect of the experiment itself. For example, suppose that gamma or neutron radiation is expected to spike during a plasma discharge. Yet the discharge may produce copious amounts of EM noise, which may be picked up by gamma and neutron detectors and reported as a spike in counts. To reduce this possibility special measures must be taken to properly screen the detectors from transient EM interference. To gain complete certainty, manual examination of the raw detector signal may be required to confirm authenticity of the counted pulses associated with the count rate spike, e.g. the pulse rise time and the exponential decay time constant must match the detector specifications.

In practice one should follow these steps to reduce or eliminate the EM noise:

- use high quality brand name coaxial cables and connectors (no cheap generics);
- troubleshoot and eliminate ground loops;
- use Faraday cages to enclose nuclear instruments: one will get the least amount of the EM interference when the entire instrument is running on battery inside of a solid metal box.

Keep in mind that no amount of EM shielding will remove all the EM interference. Unfortunately, it is a common misconception that a Faraday cage eliminates all electric fields. Electrodynamics is a complex phenomenon and transient electromagnetic fields can and occasionally will make themselves known even inside a solid Faraday enclosure. Because no amount of screening can eliminate all possible electromagnetic interference additional measures must be taken in order to ensure that the detected signal is indeed genuine.

8. Pulse Height Spectrum

Examination of the pulse-height spectrum produced by a detector can provide additional clues on whether the counted pulses are genuine. For example, some detectors generate pulses of varying amplitude regardless of their ability to measure the particles' energy. Such detectors will produce the same pulse-height spectrum shape for all measurements. A deviation from the usual shape is an indicator of a problem such as noise or malfunction. A ZnS(Ag) scintillation detector for alpha/beta particle counting is a good example of this behavior, its pulse height spectrum is shown on Fig. 3.

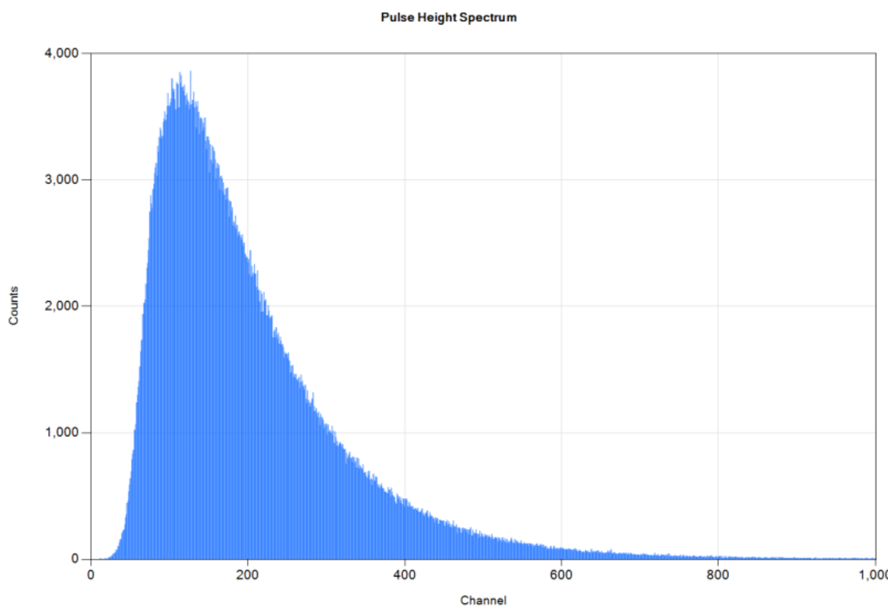

Fig. 3. The pulse height spectrum of a ZnS(Ag) scintillation detector.

If there are any unexpected peaks present on such a spectrum, or the overall shape of the spectrum is different then the measurement was compromised by noise and therefore must be redone.

Another indicator of noise are spectral peaks corresponding to energies that are too high or too low for the detector specifications. For example, most gamma scintillation detectors are packaged in aluminum or steel enclosures and thus are not sensitive to gammas below 20 keV. If a spectrum captured using such a detector exhibits a peak below 20 keV, this peak is likely to be an artifact of noise.

By the same token SDD, SiPIN and Si(Li) detectors are generally not sensitive to x-rays above 40 keV. Thus, if an x-ray spectrum acquired using an SDD has significant peaks with energies much greater than 40 keV, those peaks are likely to be artificial as well.

Therefore having the ability to plot and inspect a pulse height spectrum provides an important diagnostic tool for evaluating the veracity of the acquired counts.

9. Statistical Analysis

9.1 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 true difference. Instead a statistical analysis must be conducted in order to determine if the two population means are in fact different (as opposed to merely appearing different due to insufficient sampling.

One such common tool for comparing populations is Student’s t-test. This test yields a numerical measure called *p-value*, which can be used to interpret statistical significance of 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 p-value less 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.

9.2 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 power of test should be also 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.

9.3 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 ($p \to 0$) 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.

10. General Protocol for High-Veracity Measurements

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

1. Properly shield instruments from electromagnetic interference, eliminate ground loops;
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, calculate the p-value;
6. If the p-value is 0.05 or less than the difference in the count rates is statistically significant;
7. To gain further certainty do the following:
    a. Evaluate the power of 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 ($p \to 0$) with the additional measurements?

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

Following these steps is a tedious but necessary process. To help researchers cope with these rigorous requirements we have developed the Automated Nuclear Lab (ANL) hardware [3] and PulseCounter Pro software [4]. The ANL and PulseCounter Pro are designed to facilitate rapid nuclear physics experimentation. The ANL hardware / software system automates most of the tasks discussed above and thus makes it easy for researchers to acquire high-quality measurements and to derive real-time conclusions pertaining to the significance of results.

Below we give two examples applying the hitherto-defined radiation measurement protocol to two common tasks: neutron and gamma detection.

11. ^{3}He Proportional Neutron Counters

^{3}He filled proportional neutron counters are the most sensitive detectors of thermal neutrons. This is the case because helium-3 has one of the highest cross-sections for capturing thermal neutrons among all known elements.

When working with neutrons it is important to remember that neutron capture cross-section varies greatly with neutron's energy: fast neutrons (i.e. neutrons with energies on the order of 1 MeV) have 10,000 lower probability of being captured by helium-3 than thermal neutrons (i.e. neutrons with energies on the order of 0.01 eV). This means that a ^{3}He filled detector is efficient only for detecting thermal neutrons as fast neutrons will go right through the detector without any interaction.

Mechanically a proportional counter is a sealed metal cylinder (cathode) filled with gas with an anode wire in the middle. The cathode is grounded while a positive bias voltage (300 to 3,000V, depending on detector design and fill pressure) is applied to the anode. When a helium-3 nucleus inside the detector absorbs a neutron it converts into a high energy proton and a high energy triton ($^3He + n^0 \rightarrow p^+ + {}^3H$) that ionize the gas inside the detector causing a temporary short between the anode and the cathode. This 'short' results in a small amount of charge being deposited onto the anode. This charge is typically integrated using a charge-sensitive preamplifier, or in the simplest case, by a capacitor - Fig. 4.

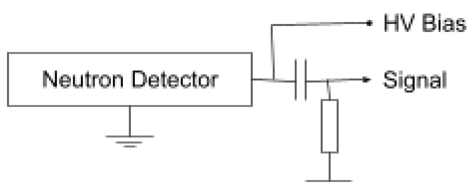

Fig. 4. The simplest electrical connection scheme for a ^{3}He-filled proportional counter.

Depending on the bias voltage and on the detector design the resulting voltage pulse can be in the range from a fraction of a millivolt to 100 millivolts, Fig. 2.

When operated as intended, a ^{3}He filled proportional neutron counter produces a thermal neutron spectrum similar to the one shown on Fig. 5.

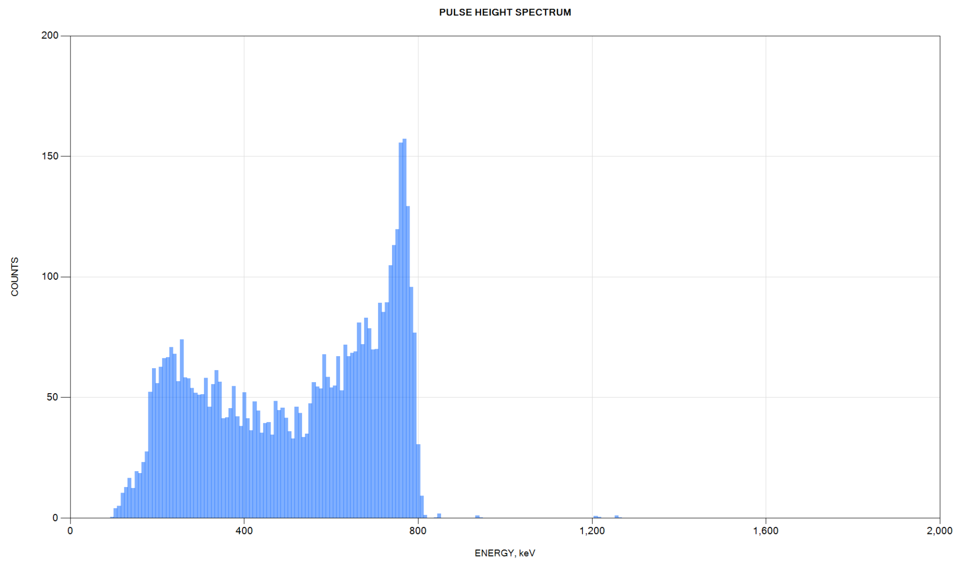

Fig. 5. A thermal neutron energy spectrum produced by a ^{3}He filled proportional counter.

This means that regardless of the source of neutrons or their initial energy the shape of the spectrum obtained using a ^{3}He counter will always be the same. This is somewhat counterintuitive because the term ‘proportional counter’ implies energy resolution. In the case of thermal neutron counters the energy resolution is somewhat fictitious in the sense that by far and large all the fast neutrons pass through the counter without being detected, it is only the neutrons that have been slowed down (i.e. thermalized) by interaction with moderator or with the environment that register, although the information about their initial energy is lost. The shape of the thermal neutron spectrum merely reflects how much energy is carried away by the proton and / or the triton upon a neutron capture by a helium-3 nucleus. On rare occasions, when a helium-3 nucleus absorbs a fast neutron, spectral channels outside the thermal neutron range will be populated. But the number of such events will be 10,000 fewer than thermal neutron events, thus deviation from the thermal neutron spectrum would be very insignificant unless the neutron flux is very large.

11.1 Moderator

Because ^{3}He filled proportional counters are highly sensitive only to thermal neutrons, a moderator should be used to thermalize / slow down fast neutrons. Any hydrogen-rich material (such as wax, oil, water, etc.) is suitable although high density polyethylene (HDPE) is the most common choice. Because hydrogen absorbs thermal neutrons, deuterated moderators (such as heavy water) will result in the higher detection sensitivity. Unfortunately deuterated materials are too expensive to be practical with the possible exception of heavy water.

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 whereas a moderator that is too thick may also result in the 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 experiment [5]. 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 to the neutron source as possible and put the moderator around both the detector and the source - Fig. 6.

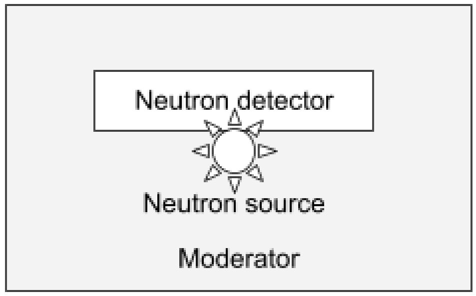

Fig. 6. The optimal neutron detector and moderator placement with respect to the neutron source.

11.2 Detector Sensitivity

^{3}He neutron detector sensitivity depends almost entirely on the solid angle covered by the detector. That is why placing the detector as close to the neutron source as possible will result in the highest count rate. From the standpoint of detector sensitivity, ^{3}He filled proportional counters have nearly identical thermal neutron sensitivity per unit area close to 100% almost regardless of the fill pressure (high fill pressure is beneficial for increasing the probability of detecting fast neutrons and for reducing the amount of moderator necessary). Neutron detector sensitivity is typically expressed in CPS/nv, where nv is the measure of neutron flux, nv = neutrons/(s cm^2). Thus, the CPS/nv characteristic of a ^{3}He proportional neutron counter is chiefly determined by the detector size.

Last but not least, it is a common misconception to state that ^{3}He filled neutron detectors are insensitive to gammas. Generally speaking, this is not true. Helium-3 detectors do register gammas, fortunately the resulting gamma pulses tend to be lower in amplitude compared to neutron pulses. Therefore a gamma peak usually can be easily separated from the neutron spectrum as shown on Fig. 7.

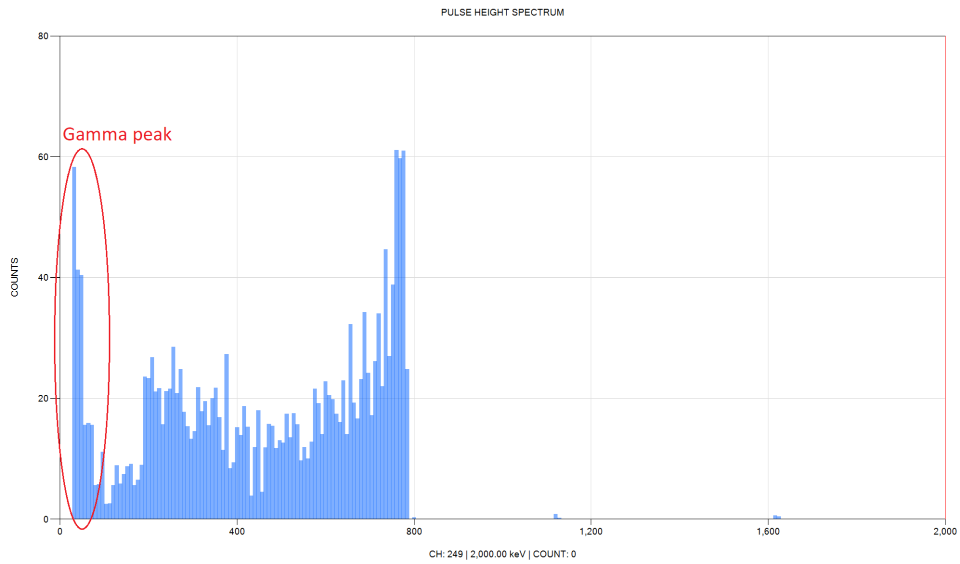

Fig. 7. Gamma peak preceding the thermal neutron spectrum.

This peak must be eliminated by raising the pulse counting threshold beyond the magnitude of the peak. This strategy works well as long as the gamma flux is low. When the gamma flux is high, the x-ray peak will become broader and will expand into higher spectrum channels thus overlapping with the thermal neutron spectrum. As such, gamma counts and gamma spectrum are ought to be monitored concurrently with neutron spectrum in order to ensure accurate separation of gammas from neutrons: when the gamma flux is high and cannot be reduced (e.g. by insulating the neutron detector with lead sheets) the neutron counting threshold must be increased to exclude the peak at the expense of excluding some of the counted neutrons also.

11.3 Neutron Background

Another common misconception pertains to neutron background. Natural neutron background is primarily caused by cosmic rays and therefore can exhibit considerable variability. Such variability is expected and should not be surprising. The cosmic neutron flux can be augmented by the weather related neutron flux, i.e. electric storms and lightning are known to generate neutrons [6]. Regardless, the shape of the background neutron spectrum reported by a ^{3}He 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.

11.4 Calibration

Neutron detectors are typically calibrated using NIST-traceable neutron sources such as Pu-Be, Ra-Be, Am-Be, or Cf-sources. Such sources are generally characterized by a few curies of activity and therefore require an NRC license to be purchased and operated.

While a NIST traceable source is necessary to precisely establish the detector sensitivity, any neutron source will do to establish the shape and to 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 ~100 hours (4 days) to acquire enough data points to resolve the shape of a thermal neutron spectrum.

Clearly, waiting for a few days is impractical, therefore 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 license [7]; such source can be paired with a beryllium window to form a neutron check-source, Fig. 8.

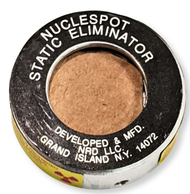

Fig. 8. Po-Be neutron check source: a Nuclespot P2042-1000 static eliminator is paired with a circular thin beryllium window covered with a brown cardboard plug.

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.

11.3 Simple Neutron Detection System

A simple neutron detection system based on the ANL is shown on Fig. 9.

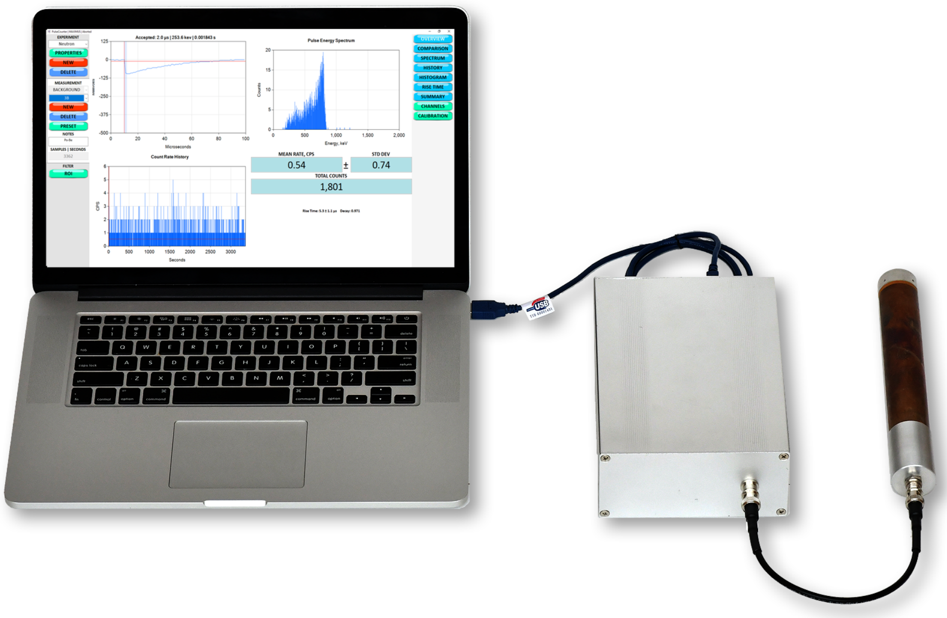

Fig. 9. An ANL-based neutron detection system.

The neutron detector configuration on Fig. 9 is the simplest possible one as it does not employ a preamp and the detector signal is digitized directly by the ANL. When a preamp is necessary an Ortec 142PC, a Canberra 2006 or a Cremat CR-11X charge-sensitive preamps can be used.

^{3}He proportional counters are typically operated using bias voltages between 1,000 and 1,500 volts and produce signals on the order of a few millivolts. The detector pulses are characterized by a rise time of about ~10 µs and can be shaped using a trapezoid filter. For best results we recommend acquiring the proportional counter signal at 1 MHz. 8-bit resolution is sufficient. The ANL hardware architecture and the PulseCounter pulse processing algorithm are described in depth in [3] and [2] respectively.

11.4 Sources of Systematic Errors

When working with ^{3}He filled proportional counter some common sources of systematic errors are as follows:

- **Ground loops:** due to the smallness of the magnitude of the detector signal (few mV) the noise from switching power supplies is often the main source of the EM interference; high quality grounding and loop elimination techniques must be used in order to eliminate this noise;
- **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 as shown on Fig. 10;

- **Vibration:** electrical contacts within the detector (e.g. the anode mounting) may be affected by mechanical vibration resulting in artificial pulses due to the intermittent loss of contact;
- **Temperature variations:** ^{3}He proportional counters are generally not sensitive to temperature variations, but depending on the age of the detector the mechanical contacts may be disrupted by non-uniform thermal expansion resulting in artificial pulses;
- **Changes in positioning** are another common source of the count rate variations: even slight movement of the detector with respect to the source or slight dislocations of the source with respect to the detector will result in perceptible, statistically significant changes in count rates when the measurement time is long;
- **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 (human body is mostly water, and water is an excellent moderator).

Fig. 10. A Neutron-Pro system featuring the entire detector hardware packaged within a solid aluminum enclosure for maximum EM interference protection.

Fortunately, artificial pulses due to systematic errors may be possible to detect by examining raw the detector signal and by verifying the shape of the thermal neutron spectrum. Any deviations from the expected pulse shape or from the expected appearance of the thermal neutron spectrum are signs of interference.

11.5 Case Study

The following example illustrates the neutron detection process discussed above performed using the ANL hardware [3] and PulseCounter Pro software [2]. In this example we used an assembly of six LND 251106 detectors arranged in a bank as shown on Fig. 11.

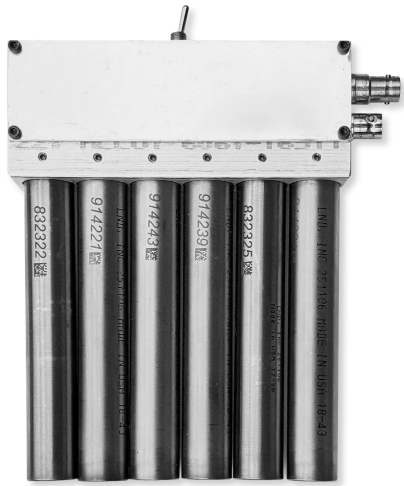

Fig. 11. The bank of six LND 251106 ^{3}He proportional counters with a builtin 9V battery-powered preamp.

The detector bank was fitted with a builtin 9V battery-powered preamp to boost the detector signal and output short (~10 μs duration) positive polarity pulses with magnitude between 1 and 100 mV. The detector bias was set to 1,050 V and the detector signal was sampled at 1 MHz / 12 bit using a PicoScope 4224A. PulseCounter Pro was used to capture and process the detector signal by integrating the pulses and rejecting all shaped pulses with amplitude below 3 mV to eliminate the gamma peak and occasional artifacts due to capacitive coupling between the detector and the piezoelectric driver used in the experiment.

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.

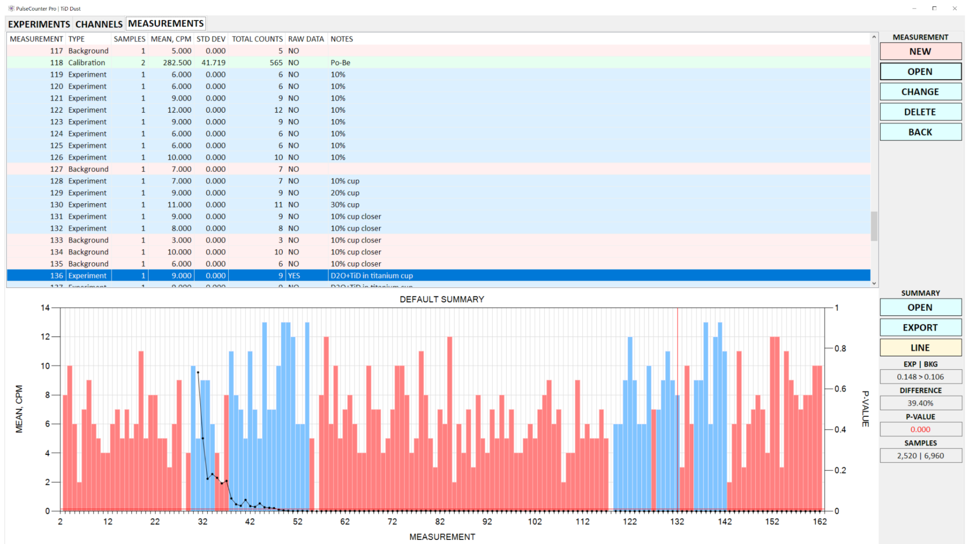

Fig. 13. The summary plot of the ‘background’ (red) and the ‘experiment’ (blue) mean count rates; the p-value trend is given by the black line.

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.

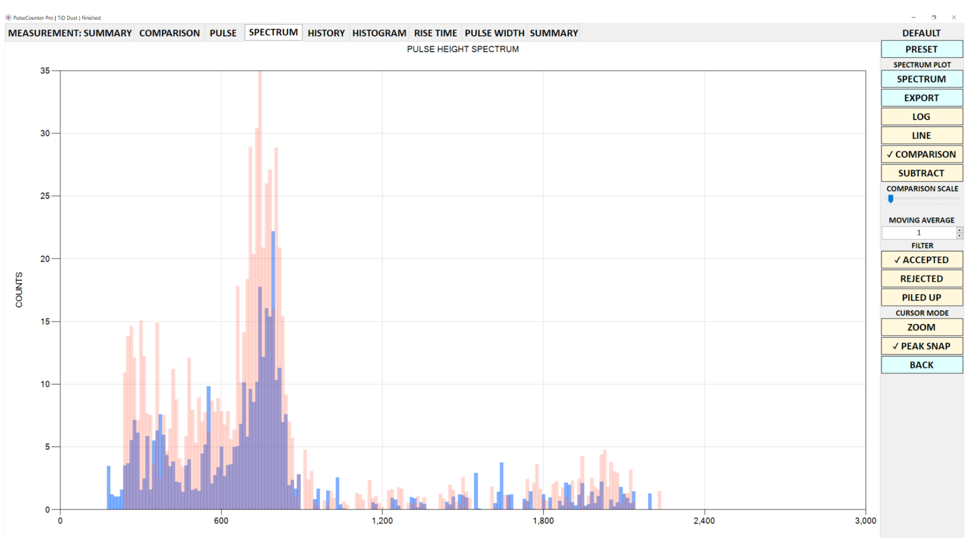

Fig. 14. The spectra of the merged ‘experiment’ and ‘background’ measurements.

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 have examined the count rate histograms and found them fitting Poisson distribution rather well (χ^2 test, $p = 0.748$), Fig. 15.

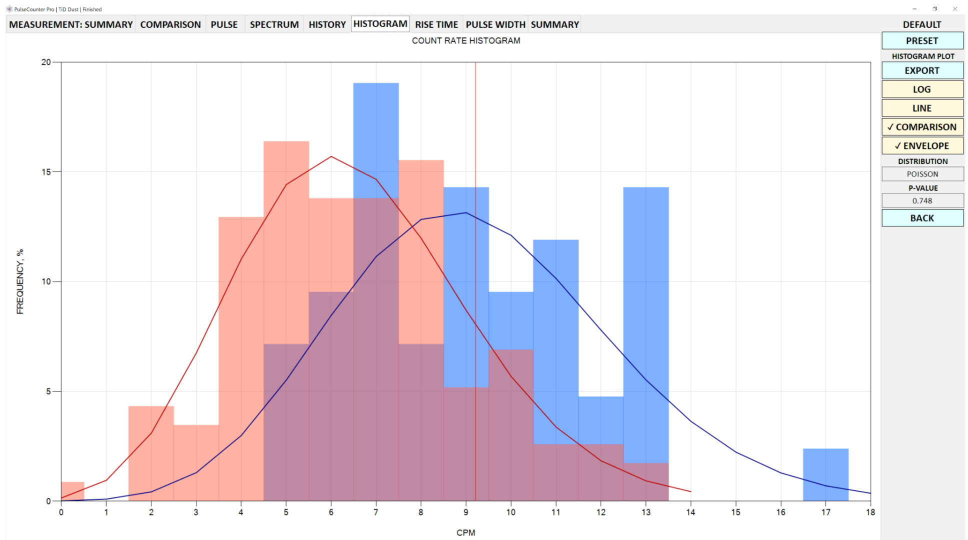

Fig. 15. The count rate histograms of the merged ‘experiment’ and ‘background’ measurements with the corresponding Poisson distribution envelopes.

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.

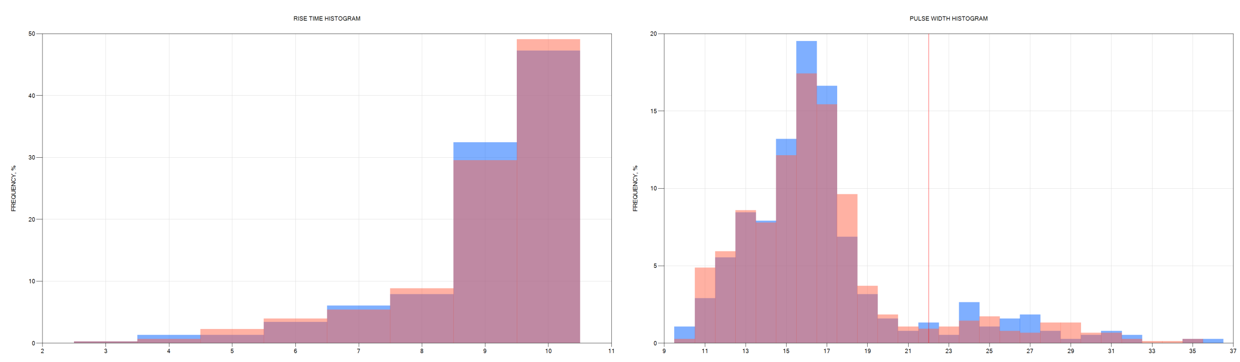

Fig. 16. The rise time (left) and the pulse width (right) histograms of the ‘experiment’ (blue) and the ‘background’ (red) measurements.

Last, but not least we have examined all counted pulses by browsing the recorded raw detector signal and did not detect any abnormalities, Fig. 17.

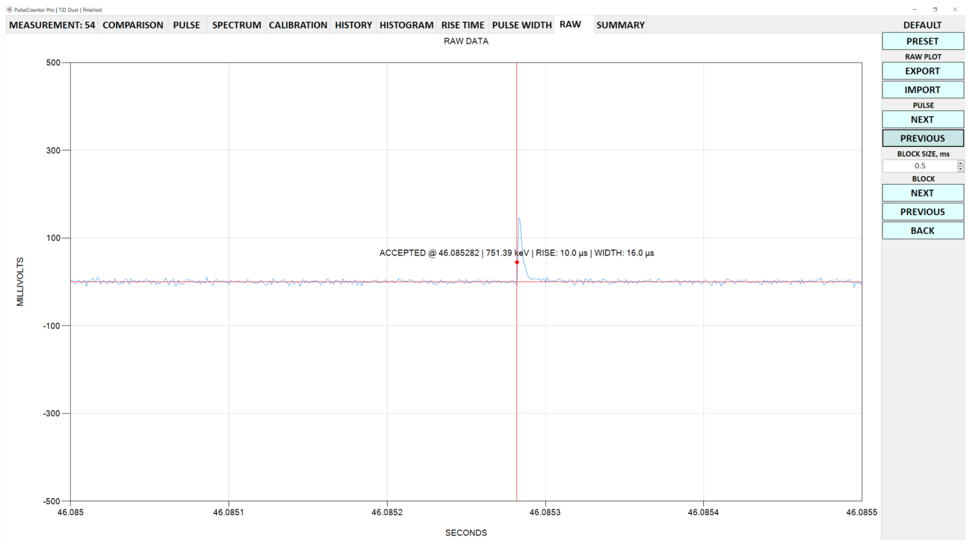

Fig. 17. Raw detector signal illustrating a single counted neutron pulse.

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 we deem this conclusion as established beyond reasonable doubt.

12. NaI(TI) Gamma Scintillation Detectors

NaI(TI) scintillators are the most common and the most widely used gamma detectors. The key component of any scintillator is the scintillation material capable of interacting with gamma quanta and producing short pulses of visible light, which are typically captured and amplified by a photomultiplier tube (PMT) or by a silicon-based photomultiplier (SiPM). In all cases, a scintillation detector is a sealed assembly comprising a scintillator material coupled to a photomultiplier - Fig. 18.

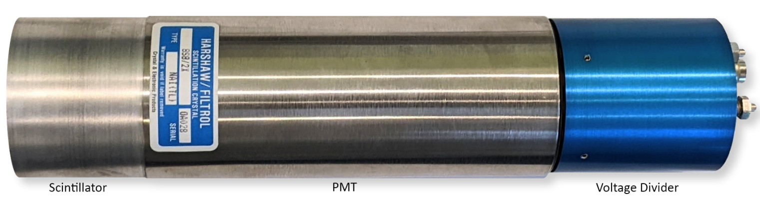

Fig. 18. A typical NaI(TI) scintillation detector comprising a NaI(TI) scintillator assembly, a PMT, and a voltage divider.

12.1 Detector Efficiency and Sensitivity

Depending on the scintillator, scintillation detectors differ in their efficiency in detecting gamma quanta of different energies. E.g. NaI(TI) scintillator efficiency peaks around 25% at 250 keV and drops below 10% at 2 MeV.

Just like in the case of proportional counters, scintillation detector sensitivity is chiefly determined by the detector size and geometry with bigger detectors being more sensitive due to the larger solid angle that they cover and due to larger volume. Thus, a scintillation detector sensitivity increases with the detector area while the detector efficiency increases with the detector volume. Therefore detectors with different scintillator size will be characterized by a different energy response: thin-scintillator detectors will produce much smaller high-energy peaks compared to thick-scintillator detectors.

Also, detector construction plays a significant role in the detector sensitivity to low-energy gammas. Because a scintillation detector must be packaged within an light-tight enclosure (typically metal), this enclosure will absorb a good deal of low energy gamma quanta. As such detectors meant for capturing low-energy gammas (such as soft x-rays) are usually fitted with a beryllium window.

12.2 Simple Gamma Detection System

A simple gamma detection system based on the ANL is shown on Fig. 19.

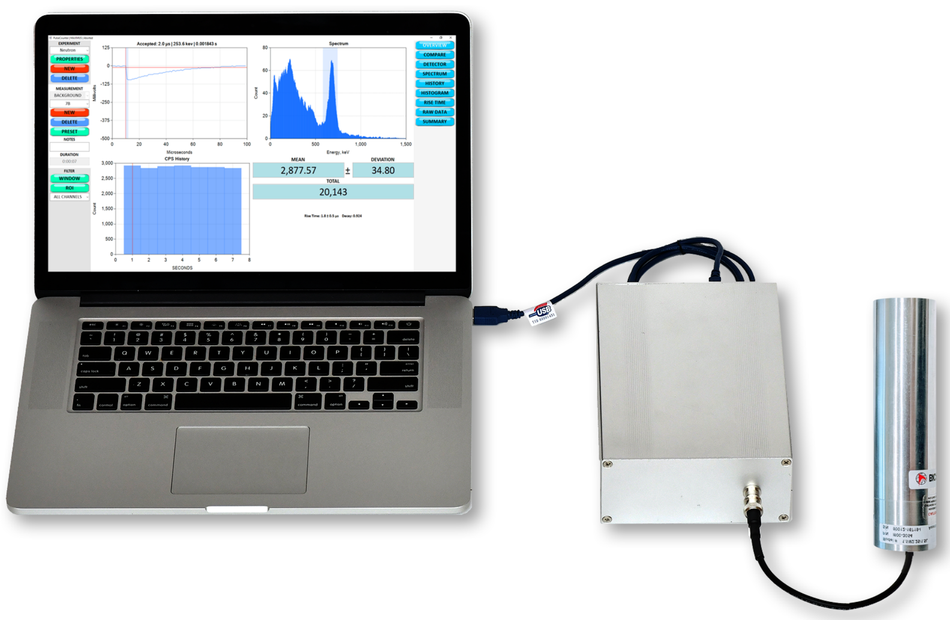

Fig. 19. An ANL-based gamma spectrometer.

The gamma detector configuration on Fig. 19 is the simplest possible one as it does not employ a preamp and the detector signal is digitized directly by the ANL. When a preamp is necessary an Ortec 113, a Canberra 2005 / 2007B, or a Cremat CR-11X charge-sensitive preamps can be used. The ANL hardware architecture and the PulseCounter pulse processing algorithm are described in depth in [3] and [2] respectively.

NaI(Tl) scintillation detectors are typically operated using bias voltage between 500 and 1,100 volts and produce signals on the order of hundreds of millivolts. The detector pulses are characterized by a rise time of about 1 μs and can be shaped using 1-μs long trapezoid filter.

For best results we recommend acquiring the scintillation detector signal at 5 MHz / 12 bit or 16 bit (16-bit digitization results in a smoother pulse-height spectrum with fewer aliasing artifacts).

12.3 Gamma Background

Natural background gamma radiation spectrum captured using a Bicron 2M2 NaI(Tl) scintillation detector is shown on Fig. 20.

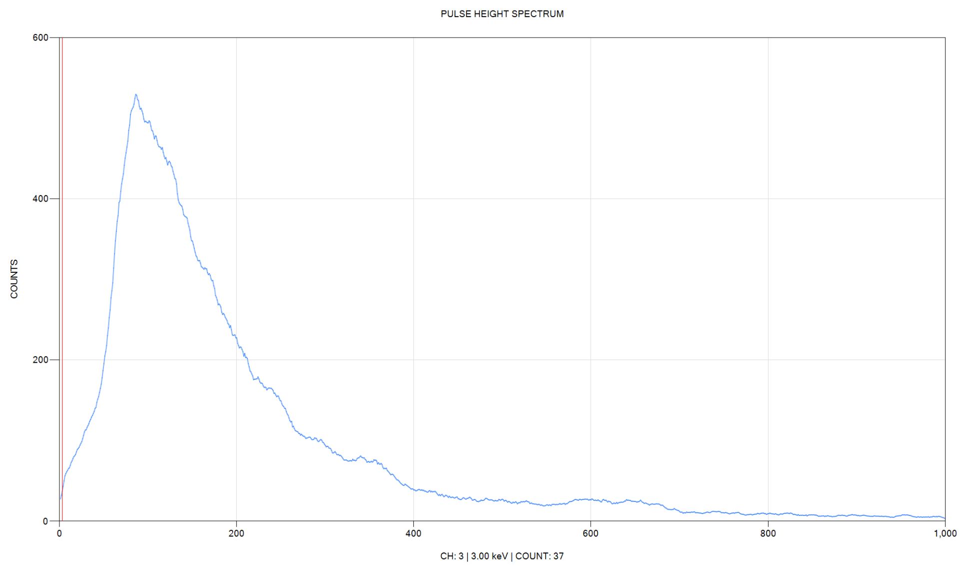

Fig. 20. Natural background gamma radiation spectrum captured using a Bicron 2M2 NaI(Tl) scintillation detector.

The shape of the background spectrum captured using different scintillation detectors will differ somewhat due to variations in the detector efficiency with energy but the overall shape of the spectrum will remain generally the same.

Gamma background can vary significantly from place to place and can be reduced by enclosing the detector in a lead shield. Keep in mind, however, that the lead shield may result in the Pb x-ray fluorescence (XRF) peaks appearing on the spectrum when the experiment is producing copious amounts of x-rays or gammas. When the XRF peaks are undesirable one can use HDPE or other carbon-based materials to reduce the background counts. Although it will take a lot more of the lighter elements to achieve the same level of screening, the light element XRF peaks primarily fall into the 0 to 20 keV range and therefore are not likely to register on the spectrum.

12.4 Calibration

All gamma detectors must be energy calibrated before use. The calibration can be performed using the exempt sources manufactured by Spectrum Techniques, Fig. 21.

Fig. 21. Spectrum Techniques except gamma calibration sources.

Different sources are recommended for different energy ranges as follows:

- 0 to 20 keV: ^{55}Fe,
- 20 to 100 keV: ^{57}Co,
- 100 keV to 1 MeV: ^{137}Cs,
- > 1 MeV: ^{60}Co.

Because NaI(Tl) detectors are not perfectly linear we recommend using multi-peak calibration (e.g. using the 32 keV and 661.8 keV lines of ^{137}Cs) or using multiple sources. Repeated calibration may be necessary due to the drift of the non-temperature stabilized detectors.

When calibrating a gamma detector it is possible to use linear (1 or 2-point), quadratic (3-point), or quadratic regression calibration (4 and more points) [4]. In the latter case the software computes the best fit given an arbitrary number of reference energies.

12.5. Sources of Systematic Errors

When working with scintillation detectors the same concerns apply as when working with ^{3}He-filled proportional counters. However, scintillation detectors are typically less sensitive to electromagnetic interference than proportional counters due to generally higher magnitude of signal that they produce (hundreds of millivolts). Still, the amount of electromagnetic interference that the scintillation detectors pick up can be reduced by sealing the gap between the PMT and the voltage divider with a 3M 1245 EMI shielding tape and by using only high quality, all-metal name brand voltage dividers such as Bicron P-14 or Canberra 2007 as cheap plastic dividers tend to be considerably more noisy.

Visible light leak is a concern specific to scintillators: no external light must penetrate into the scintillation material. Light contamination can be easily detected when the detector signal is monitored with an oscilloscope: the signal character and magnitude should not change when the detector is placed into or removed from a light-tight enclosure.

Perhaps the biggest problem using scintillators is the detector signal magnitude drift with temperature. For this reason some detectors are fitted with thermocouples and circuitry to automatically adjust the PMT gain to match the temperature variations. Other detector designs involve a heat source and / or insulation for temperature stabilization. The signal magnitude drift due to temperature is particularly problematic when working on detecting small count rate changes because the detector pulses can systematically shift above or below the pulse discrimination threshold thus significantly affecting the counts across measurements. Therefore temperature stabilization, temperature-driven gain compensation and frequent calibration is indispensable when looking for small changes in gamma count rates.

Another often overlooked source of systematic errors is natural radioactivity present in common substances, including construction materials (e.g. granite), dust, certain alloys and even air (radon). Radon contamination is particularly tricky since radon decay products tend to be attracted to high voltage electrodes that are openly exposed to air where they form quasi-permanent deposits manifesting themselves as radioactive 'hot spots'. Fortunately, radon contamination can be identified via the presence of the characteristic ^{212}Pb and ^{214}Pb daughter product gamma peaks.

Just like in the case of neutron detectors, changes in positioning of the detector or the source, rearrangement of components or movement of personnel in the vicinity of the measurement setup may also result in systematic errors in the count rate measurements due to the background screening and / or changes in distance or orientation between the detector and the source.

Last but not least, NaI(Tl) scintillators tend to degrade with time due to moisture penetration. A good NaI(Tl) scintillator crystal must appear perfectly transparent / clear upon a visual examination. Yellow scintillators indicate moisture. The moisture-related scintillator degradation reduces the detector sensitivity and resolution over time.

Conclusion

In this paper we have examined the issues and specifics pertaining to radiation detection and presented a general protocol for high-veracity measurements. We have further expanded the protocol to derive a robust methodology for reliable neutron and gamma detection using ^{3}He proportional counters and NaI(Tl) scintillation detectors. Backed by extensive statistical analysis and exhaustive sanity checks the presented measurement and data analysis methodology allows for reliable identification of small (on the order of a few percent) changes in the mean count rates between the 'experiment' and the 'background' measurements and works well for very low count rates (on the order of a few CPM). The presented measurement technique was implemented in PulseCounter Pro software and can be effectively used with the ANL. We encourage the research community to adopt the presented protocol as it allows for reliably deriving high-veracity conclusions pertaining to the presence or absence of radiation in a nuclear physics experiment.

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