Automated Nuclear Lab and PulseCounter Pro: The Tools for Rapid Nuclear Experimentation

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Abstract

Experimental nuclear physics is an exciting area of scientific research replete with unexpected discoveries that may lead to transformational advances in the fields of energy, transportation, and materials science. Until now experimental nuclear physics required cumbersome and often prohibitively expensive tools to acquire, process, and analyze detector data thus making nuclear research a slow and labor intensive process requiring expert knowledge in the areas of nuclear instrumentation, electrical engineering, signal processing, and statistical analysis. To address this problem we have developed the Automated Nuclear Lab (ANL) hardware and PulseCounter Pro software, the tools for rapid nuclear experimentation. Built using inexpensive off-the-shelf components the ANL automates key tasks involving neutron and gamma radiation detection including raw detector signal acquisition, pulse counting, signal processing, spectroscopy, and statistical analysis. By providing a carefully engineered, streamlined workflow, the PulseCounter Pro software allows deriving highly accurate, auditable, fully logged, re-analyzable, and ultimately conclusive results in real time and with minimum effort. We hope that systematic adoption of the hitherto presented protocols by the experimental nuclear physics community will lead to the accelerated rate of discovery and to the increased quality of published results.

1. Motivation

Our motivation for this work originated from the complexity of hardware and protocols conventionally employed in experimental nuclear physics. Our frustration was further exacerbated by the poor quality of the great number of published results, which we posit originates from the general lack of understanding of fundamental principles of radiation detection by the research community at large. While numerous papers are being published citing neutron, gamma, x-ray or other charged particle emissions as evidence of purported and often novel nuclear processes, we find most such results either unconvincing or outright invalid. Here are some reasons why this is often the case:

- Researchers often do not follow (or are not aware of) proper radiation detection protocols;
- Researchers often do not possess sufficiently good understanding of detector operating principles, which leads to the
- Ignorance of systematic errors and sources of noise affecting measurements;

- Counter-intuitive nature of quantum mechanics and poor knowledge of probability theory leads to the lack of comprehension of the random nature of nuclear processes; these random processes can only be understood with the help of
- Statistical analysis, which is more often than not missing from the discussion of results.

Clearly the majority of papers published in top tier journals do not necessarily suffer from these shortcomings because a publicly funded work by a large team of scientists almost always involves experts in all the above mentioned fields. Additionally, virtually all significant research projects are accompanied by rigorous peer review that takes place throughout the life of the project with the publication-related peer review being merely a formality. Such continuous peer review is typically conducted by experts specializing in individual components pertaining to a particular experiment (such as detectors, pulse processing hardware and algorithms, statistical analysis, etc) and it plays a significant role in elimination of unobvious errors or inaccuracies.

The problems, however, arise when research is conducted by small, underfunded groups that lack the resources or clout necessary to attract the required expertise. Therefore it is our goal to help elevate the quality of work conducted by and reported upon by such disadvantaged groups. We also believe that well funded, more experienced teams will benefit from the forthcoming discussion as the system that we are about to discuss is designed to reduce the costs and to increase productivity by streamlining / simplifying the hardware and by automating common tasks associated with radiation detection.

2. The ANL Hardware Architecture

A variety of brands such as AmpTek, Mirion, Canberra, Caen, Ortec, etc. offer modern, state-of-the-art nuclear instruments and a broad variety of hardware and software. These brands are staples of top tier nuclear physics projects with multi-million budgets. Regrettably, the intense competition for funding leaves many researchers severely constrained in their equipment purchasing ability and thus makes them reliant on older, outdated, and often unreliable instruments. It is not unusual to find 30-40 year old analog systems (e.g. NIM crates, circa 1970 preamps, and obsolete liquid nitrogen cooled detectors) still being used in many laboratories.

Fortunately, there is a way to leverage modern technology on a very moderate budget by employing inexpensive, mass-produced, off-the-shelf components that together with custom software can rival the quality and performance of top hardware offerings by the leading brands.

We began developing the solution by recognizing the fact that all modern nuclear instruments contain a custom signal acquisition and processing core. Rather than designing our own hardware to accomplish this task we conducted a market research and determined that the necessary hardware is already commercially available, mass produced, and quite affordable.

Specifically, we chose digital USB oscilloscopes manufactured by Pico Technology as a signal acquisition and processing core. Digital USB oscilloscopes such as PicoScopes 2000, 3000, 4000, or 5000 series are well suited for this task as they satisfy the following selection criteria:

- Adjustable input signal range from ±10 mV to ±10V;
- High analog signal digitization resolution from 12 to 16 bit;
- High sampling rate from 1 to 20 MHz;
- High, artifact-free digitization quality;
- Low intrinsic noise;
- Data acquisition in ‘streaming mode’ allowing for continuous, gap-free capture;
- Availability of an API / SDK for custom software development;
- Low cost (<$1,000).

Additional lesser important criteria are:

- The ability to capture signals on multiple channels;
- Availability of auxiliary outputs.

While there are many digital oscilloscopes, digitizers, and data acquisition boards on the market, we found that only the offerings by Pico Technology satisfy these requirements. Specifically, most lower priced 3rd party products failed to provide either the required resolution or the desired dynamic range, or did not support data streaming at a sufficiently high sampling rate. Some products (such as digital USB oscilloscopes by Virtins Technology) suffered from poor signal digitization quality not mentioned in the device specifications. Obviously, the low cost requirement excluded a great number of excellent hardware on the basis of unaffordability.

Upon selecting the PicoScope products to be used as a signal acquisition and processing core we conducted a review of available compact, low power / low cost high voltage (0 to 3,000V) regulated power supplies to provide the detector bias. We have learned that XP Power manufactures very compact Q-series DC to HVDC converters [1] that are used in many commercial instruments. For example an XP Power Q15-5 adjustable 0..+1,500V, 0.5 Watt / 333 μA max power supply can be purchased for ~$200 from Mouser Electronics.

However, we opted to commission a custom adjustable 0 to 3,000V / 0.5 mA max DC-DC converter with a 0 to 2V control signal and +5V DC input power from Analog Technologies (www.analogtechnologies.com). This custom power supply was redesigned by the manufacturer to meet our stringent intrinsic noise requirements. It is powered from USB and can be controlled by a PicoScope arbitrary waveform generator (AWG) set to output a DC voltage in the range of 0-2V.

Alternatively, an external power supply such as Ortec 556 can be used when currents up to 10 mA are necessary or when there is a need for a very low ripple / low noise linear power supply.

Finally, the high adjustable dynamic range and very low intrinsic noise of the PicoScope devices proved that for most applications involving SiPM or PMT scintillators and proportional counters we can eliminate a preamp because even a very weak detector signal (~few millivolts) can be successfully and accurately digitized by a PicoScope.

A hardware-based shaping amplifier also proved unnecessary as all the pulse shaping and signal processing tasks can be performed in software once the raw detector signal is digitized.

These findings allowed us to further simplify the design leading to the ANL block diagram shown on Fig. 1.

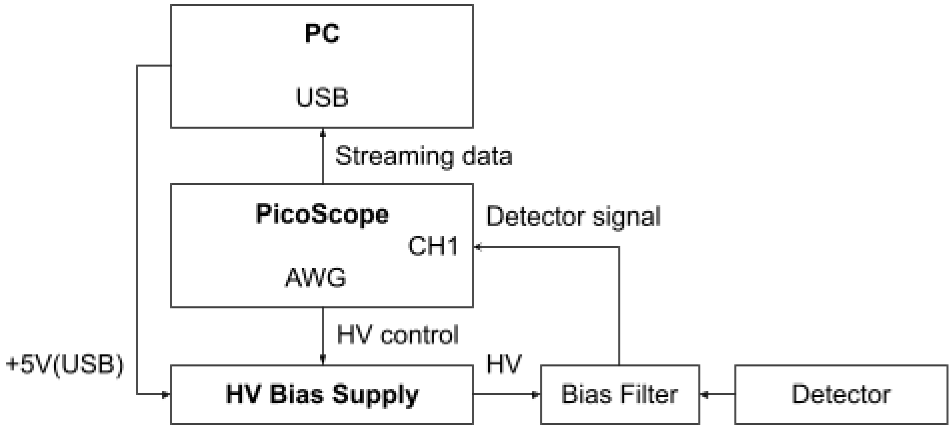


Fig. 1. The ANL hardware block diagram.

For a choice of PicoScope we recommend a 12-bit 4224A (~$1,000), a 16-bit 4262 (~$1,500) or any 5000-series instrument ($1,300-$2,500). Even an entry-level 8-bit 2000-series PicoScope (~$150) is perfectly suitable for applications involving neutron counting or medium resolution gamma spectroscopy.

To complete the ANL setup we connect a PicoScope to a PC via a USB 2.0 or better yet via a USB 3.0 port as the latter offers much higher throughput and greater current capacity, which is necessary to power the PicoScope and the power supply, which we typically connect to the same USB port via a USB hub or a USB power splitter cable. Finally, we connect the AWG output of the PicoScope to the power supply control input for voltage control. The resulting sample ANL assembly is shown on Fig. 2.

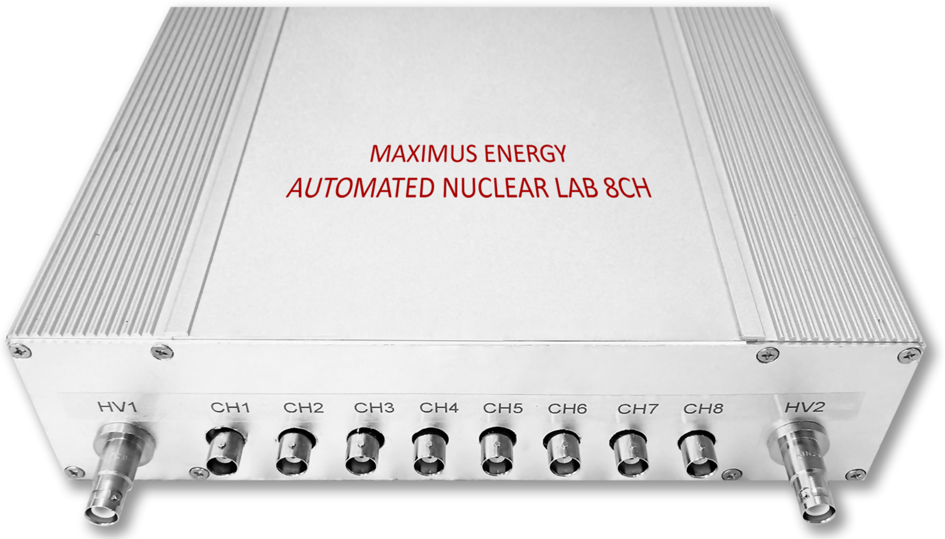


Fig. 2. A sample ANL configuration with two HV bias supplies and 8 input channels.

The ANL configuration on Fig. 2 features two HV bias supplies and 8 input channels made possible by a PicoScope 4824A. The added benefit of the PicoScope is the ability to capture analog signals on multiple channels thus making it possible to acquire sample-accurate, time-synchronous data from several different detectors or analog sensors at the same time. This could be extremely useful for correlating radiation counts to each other or to an external influence.

The presented hardware configuration is extremely simple and contains the least amount of individual parts. Strictly speaking, using a PicoScope digital USB oscilloscope connected to an external power supply is sufficient - Fig. 3.

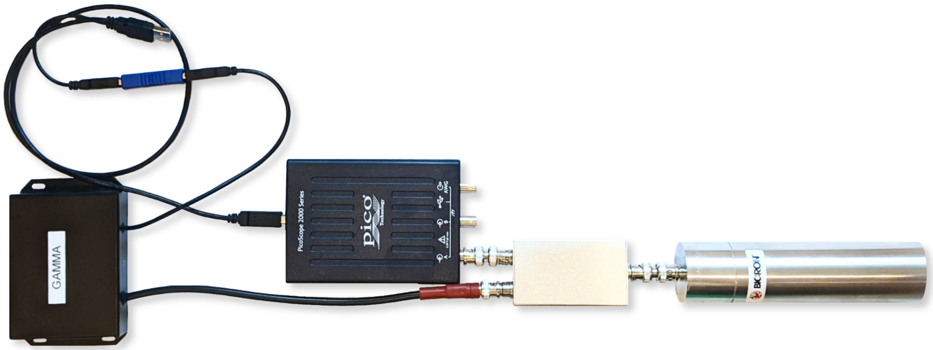


Fig. 3. A 'barebone' ANL configuration with an external power supply; a NaI(TI) gamma scintillation detector is connected to the PicoScope 2204A via a bias / signal filter.

This minimalist architecture is by design. The intent is to capture the raw detector signal in its entirety and process it in software thus eliminating as many points of failure as possible. The bare minimum number of components reduces possibilities for catching electromagnetic interference thus significantly limiting the range of instrument-related errors.

A sample complete ANL configuration with two ^{3}He proportional neutron counters and two NaI(TI) gamma scintillation detectors is shown on Fig. 4.

Fig. 4. A sample complete ANL configuration with two ^{3}He proportional neutron counters and two NaI(Tl) gamma scintillation detectors.

To summarize, a typical set of specification for an ANL system is:

- Analog signal acquisition channels: 2, 4, or 8;
- Resolution: 8, 12 or 16-bit;
- Sampling rate: 0 to 40 MHz;
- Bandwidth: 10 MHz to 1 GHz;
- Signal ranges: ±10 mV to ±20V (typical);
- Input impedance: 200 kOhm / 8 pF or 1 MOhm / 19 pF;
- Bias supply: 0 to +3,000 V / 0.5 mA max;
- USB 2.0 or USB 3.0 connectivity.

4. Connecting Detectors

Most nuclear detectors produce current or voltage pulses corresponding to the detected nuclear particles / radiation. Detectors that produce current pulses usually employ charge-sensitive preamplifiers integrating the currents and converting them into voltages. Detectors capable of energy resolution generate pulses with magnitude proportional to the energy of the detected particles. Some detectors produce pulses with different rise time depending on the type of particle detected (e.g. gamma or neutron).

The modern approach is to digitize detector signal and process it in software to detect and count pulses, discriminate between genuine pulses and noise, reject pulses on the basis of their shape or rise time, and when appropriate recover the pulse energy. All of these tasks can be efficiently performed in real-time on an ordinary PC on multiple channels and at fairly high sampling rates [2].

Depending on the connected detector and in order to optimize the performance and quality of digital pulse processing the ANL allows setting an appropriate signal range (±10 mV to ±20V), selecting the required sampling rate (usually between 0.5 and 20 MHz), choosing between the AC or DC coupling, and specifying the requisite bias voltage. Thus, each detector generally requires its own configurational preset. This flexibility allows using a wide variety of alpha, beta, neutron, X-ray, and gamma detectors / counters with the ANL.

Some detectors come with two connectors: an SHV or an MHV for high voltage bias input and a BNC for signal output, Fig. 5.

Fig. 5. A gamma detector with an SHV bias-in and a BNC signal-out connectors.

These dual-socket detectors can be connected directly to the ANL by feeding the detector signal into the first available ANL input channel via a BNC cable as shown on Fig. 4. The detector bias is supplied via a separate SHV cable.

Other detectors come with a single SHV, MHV or BNC connector that combines high voltage bias with the detector signal - Fig. 6.

Fig. 6. A neutron proportional counter with a single signal / bias SHV connector.

Such single-socket detectors can be used with the ANL by way of a splitter, which is a simple DC filter separating the HV bias from the low-voltage detector signal - Fig. 7.

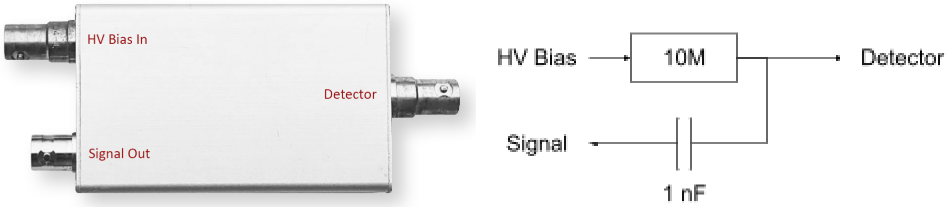


Fig. 7. (Left) A bias / signal splitter; (Right) a typical filter circuit.

When making a splitter (or any other socket adapter or cable assembly to be used with the ANL) it is important to use only the highest quality name-brand RF connectors such as Amphenol, TE Connectivity or Kings Electric and avoid using cheap unbranded generic types as the latter are prone to the increased level of electromagnetic noise, which will negatively impact the quality of the digital pulse processing algorithm. For the same reason it is also important to employ only metallic enclosures and to use 3M 1181 or 1183 EMI shielding tape to cover all gaps and seams.

The ANL provides a built-in power supply that can be used for detector bias. This bias can be shared across multiple detectors provided that all of the detectors can operate at the same bias voltage and the maximum total current draw does not exceed 0.5 mA. When the same bias voltage is shared across several detectors connected to different ANL input channels it is not necessary to adjust the bias voltage precisely. Instead it is best to tune each detector’s software preset to ensure the optimal signal processing performance and match / calibrate the detector spectrum when appropriate.

When detectors connected to the ANL require vastly different bias voltages separate external power supplies such as Caen N472 should be used.

5. General Software Design Considerations

Availability of API / SDK was one of the main considerations for selecting the Pico Technology hardware. PicoSDK provides an extensive API for controlling all aspects of signal acquisition using PicoScope devices, including wrappers and sample code for C++, C#, Python, and LabView [3].

The key requisite feature of PicoSDK and the PicoScope hardware is the availability of ‘streaming mode’, which allows for continuous, gapless acquisition of signal. Given efficient coding, real-time signal acquisition rates up to 10 MHz are possible on most PC configurations. Gapless streaming data acquisition at rates up to 40 MHz (or even higher) is also possible on PicoScope 5000 or 6000-series devices, although such signals may be acquired and communicated via USB somewhat slower than in real time.

An alternative approach, which is far more prevalent among other digital oscilloscopes, is signal acquisition in 'block mode' when a trigger is set up to capture a block of samples at a desired sampling rate. This approach is considerably simpler to implement in software, and in the case of PicoScope, the 'block mode' allows for very high sampling rates, up to 1 GHz. However, we found the 'block mode' approach unsatisfactory for the following reasons:

- There will always be gaps associated with the triggering mechanism and time taken to capture and transmit the data; such gaps may contain critical events and thus limit the detection efficiency;
- Reliable triggering may be difficult to set up, especially when the detector signal is DC-coupled, and particularly when the detector signal corresponds to a reset-preamplifier ramp.

Therefore we find the 'streaming mode' requirement of critical importance for maximum generality and best performance. Fortunately, even low-end CPUs nowadays provide sufficient performance for real time pulse processing of signals acquired at 5 MHz or even at 10 Mhz sampling rate.

PicoScope streaming mode supports multiple buffering with the acquired data stored continuously in a sequence of software buffers in computer memory. This enables software code to que the buffers for acquisition and processing such that when one buffer is being processed the other buffer is being acquired, thus avoiding performance bottlenecks and fatal buffer overwrites. Furthermore, PicoScope devices feature rather significant hardware buffers (up to 512 megasamples), which make gapless data acquisition possible regardless of delays associated with the PC signal processing or the USB data transmission bottlenecks.

PicoSDK comes with numerous code samples illustrating how to set up data acquisition and acquire data in streaming mode. These samples are intended to serve as a starting point for custom software development.

Regardless of the chosen language, platform, or signal processing algorithm the software must report the following information as a result of a 'measurement':

- A sequence of count rate samples;
- Mean count rate and standard deviation;
- Pulse height or pulse energy spectrum (when appropriate);
- Count rate histogram.

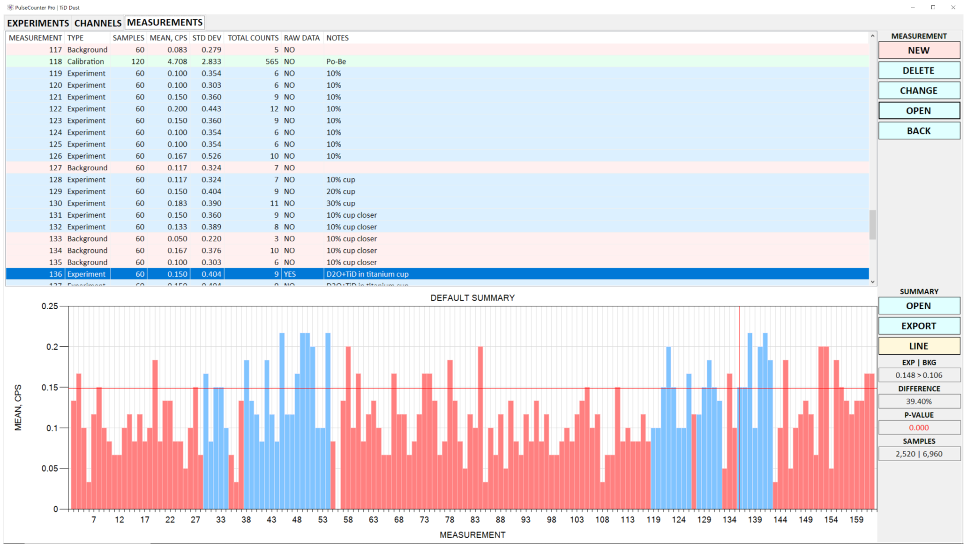
Keep in mind that a single measurement is never sufficient to derive a meaningful conclusion [4]. Therefore software must support acquisition of multiple measurements that must be subjected to a statistical analysis in order to interpret the results [4].

6. PulseCounter Pro Software

To make the ANL function we have developed the proprietary PulseCounter Pro software [5]. The software is written in C# using \ PicoSDK and requires a Windows PC to run. The software uses the PusleCounter digital pulse processing algorithm, which is described in detail in [2].

PulseCounter Pro software (Fig. 8-9) performs the following tasks:

- Configures the ANL for a specific experiment by specifying which detector or analog sensor is connected to which channel and how each channel's data is supposed to be acquired and processed;
- Acquires 'calibration', 'experiment' or 'background' measurements organized in 'experiments';
- For each measurement records the count rate history and computes the count rate, the pulse width, and the rise time histograms as well as the pulse height (or the pulse energy) spectrum;
- Computes the count rate mean and the standard deviation, fits the count rate histogram to a Poisson distribution and reports the quality of the fit;
- Allows calibration of the pulse-height spectrum using an arbitrary number of the reference energy points;
- Allows recording raw detector signals for inspection and off-line measurement reanalysis using a different signal processing algorithm or a different set of pulse acceptance / rejection criteria;
- Allows browsing and inspection of signal shapes associated with the individual accepted or rejected detector pulses;
- Allows comparing measurements;
- Calculates statistical significance of results (Student's T-Test and p-value) by comparing populations of the 'background' and the 'experiment' measurements;
- Allows aggregating, correlating and merging counts and spectra acquired from different detectors.



MEASUREMENT	TYPE	SAMPLES	MEAN, CPS	STD DEV	TOTAL COUNTS	RAW DATA	NOTES
117	Background	60	0.083	0.279	5	NO	
118	Calibration	120	4.708	2.833	565	NO	Po-Be
119	Experiment	60	0.100	0.354	6	NO	10%
120	Experiment	60	0.100	0.303	6	NO	10%
121	Experiment	60	0.150	0.360	9	NO	10%
122	Experiment	60	0.200	0.443	12	NO	10%
123	Experiment	60	0.150	0.360	9	NO	10%
124	Experiment	60	0.100	0.354	6	NO	10%
125	Experiment	60	0.100	0.354	6	NO	10%
126	Experiment	60	0.167	0.526	10	NO	10%
127	Background	60	0.117	0.324	7	NO	
128	Experiment	60	0.117	0.324	7	NO	10% cup
129	Experiment	60	0.150	0.404	9	NO	20% cup
130	Experiment	60	0.183	0.390	11	NO	30% cup
131	Experiment	60	0.150	0.360	9	NO	10% cup closer
132	Experiment	60	0.133	0.389	8	NO	10% cup closer
133	Background	60	0.050	0.220	3	NO	10% cup closer
134	Background	60	0.167	0.376	10	NO	10% cup closer
135	Background	60	0.100	0.303	6	NO	10% cup closer
136	Experiment	60	0.150	0.404	9	YES	D2O+TiD in titanium cup

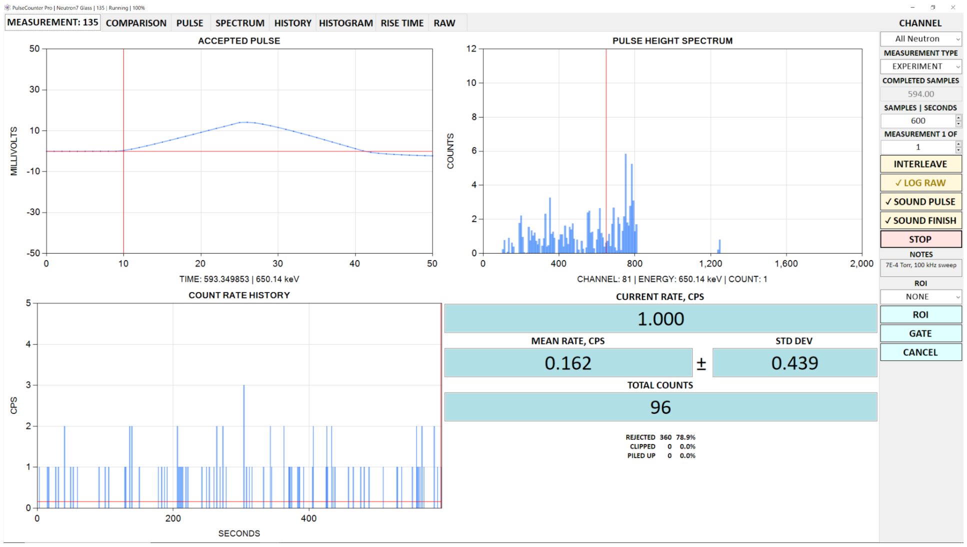
EXP | BKG: 0.148 > 0.106

DIFFERENCE: 39.40%

P-VALUE: 0.000

SAMPLES: 2,520 | 6,960

Fig. 8. PulseCounter Pro software screenshot illustrating multiple measurements including the result of their statistical analysis.



PulseCounter Pro | Neutron7 Glass | 135 | Running | 100%

TIME: 593.349853 | 650.14 keV

CHANNEL: 81 | ENERGY: 650.14 keV | COUNT: 1

CHANNEL: All Neutron

MEASUREMENT TYPE: EXPERIMENT

COMPLETED SAMPLES: 594.00

SAMPLES | SECONDS: 600

MEASUREMENT 1 OF: 1

NOTES: 7E-4 Torr, 100 kHz sweep

ROI: NONE

CURRENT RATE, CPS: 1.000

MEAN RATE, CPS: 0.162 ± STD DEV: 0.439

TOTAL COUNTS: 96

REJECTED	360	78.9%
CLIPPED	0	0.0%
PILED UP	0	0.0%

Fig. 9. PulseCounter Pro software screenshot illustrating the details of a single measurement.

Conclusion

In this paper we have described the Automated Nuclear Lab (ANL), a hardware / software system for rapid nuclear physics experimentation. The hardware portion of the system can be built from off-the-shelf components on a very limited budget, e.g. by using PicoScope hardware for signal acquisition and any 3rd party high voltage power supply for detector bias. The unique hardware / software architecture of the ANL allows acquisition and processing in real time of signals from up to 8 different nuclear instruments and auxiliary analog sensors, such as proportional counters, scintillators, solid-state detectors, or HPGe systems. When powered by PulseCounter Pro software, ANL automates nuclear physics experiment workflow, including recording, processing, analyzing, and evaluating statistical significance of results.

By freeing up time and resources the ANL and PulseCounter Pro allow one to focus on what is really important: design and execution of the experiment. In other words, the ANL is designed to reduce costs and increase productivity by helping researchers to run more experiments in less time.

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