PAPER

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The Zener diode: generating gamma-ray statistics without the gamma rays

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Abstract

Here we demonstrate an inexpensive and straightforward electronic circuit that can be used to generate data in the form of counts, with the same statistical properties as those found in gamma-ray counting experiments. The circuit holds an avalanche Zener diode just below its Zener voltage, which allows for thermal electrons to traverse the in the Zener's PN junction, causing sporadic conduction events lasting ∼10 ns. If counted in a manner similar to gamma-ray arrivals, we show the conduction events will follow identical statistical distributions as the gamma-rays.

Keywords: Zener, diode, statistics, gamma-ray, electonics, circuit, arduino

1. Introduction

Those experienced with a university's advanced lab curriculum in physics are undoubtedly familiar with gamma-ray scintillation experiments [1]. With a suitable source and scintillation detector, one can perform counting experiments, where a scalar delivers the number of gamma-rays detected in some time interval. After compiling a list of many such numbers (or 'counts'), subsequent data analysis lessons involve histograms, the binomial, normal and Poisson distributions, curve fitting, and chi-squared analysis [2].

The intent of this article is to demonstrate an inexpensive (∼$20 USD) electronic circuit that delivers the same statistically relevant data as a gamma-ray source. Here, the source of events is not from nuclear emissions but avalanche conduction of a Zener diode. Likewise, the data acquisition is not driven by nuclear instrumentation modules, but an Arduino with a suitable sketch loaded.

2. The Zener diode

The Zener diode is a specially constructed diode when reverse biased, does not conduct when an applied voltage is below the so-called the 'Zener voltage' (which is device specific). It does conduct however, when the applied voltage exceeds the Zener voltage. The Zener is able to recover from to its nonconducting state once the applied voltage

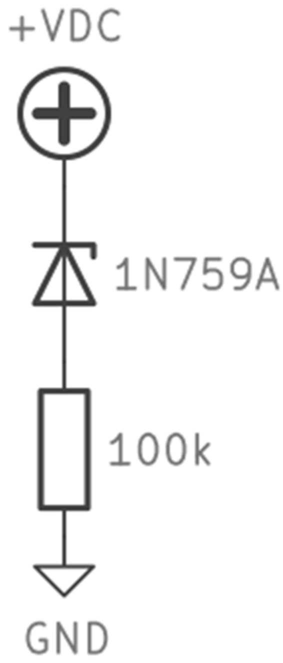

Figure 1. Circuit to illustrate avalanche breakdown of the Zener diode.

goes below the Zener voltage again. Typically, Zener diodes find uses as voltage regulators and as protection shunts at the input to downstream circuitry.

In this work, we begin with the circuit shown in figure 1, which was motivated by work done in the area of developing a hardware random number generator [3]. In this figure, the 1N759A is an avalanche Zener diode, with a Zener voltage of 12.1 V [4]. An adjustable voltage is applied across the Zener-resistor series, slowly approaching the Zener voltage starting from about 10 V, while monitoring the voltage across the resistor with a line-triggered oscilloscope. When the voltage hits about 11.9 V (notably below the Zener voltage), an oscilloscope captures the trace shown in figure 2.

The 'spikes' shown are brief avalanche conduction events in the Zener diode. They are caused by a thermal electron near the PN junction getting swept up by the electric field created by the applied voltage. The electron collides with crystal structure of the PN junction, causing still further electrons to become loose, hence the work 'avalanche.' The appearance of conduction spikes initiated by a thermal electron is completely random, much like the emission of a gamma-ray. To generate counts akin to gamma-ray counts, the number of spikes occurring in some time interval must be counted, and made available for recording.

3. Determining counts

To count the spikes in some time interval, an Arduino is used to mimic the role of a scalar in nuclear counting experiments. We thus proceed as shown in figure 3, which routes the conduction spikes into an LM311 comparator. The reference voltage for the comparator is set to about 50 mV using the 100:1 voltage divider on input to pin 3. The spikes are fed into pin 2, which will cause the LM311 to swing from ground to its supply voltage (+5 V) when a spike amplitude exceeds the reference voltage. The LM311's open collector output is tied to +5 V on the Arduino using a 1k pull-up resistor. Lastly, the 1nF DC-blocking capacitor removes a small DC offset, forming an output of

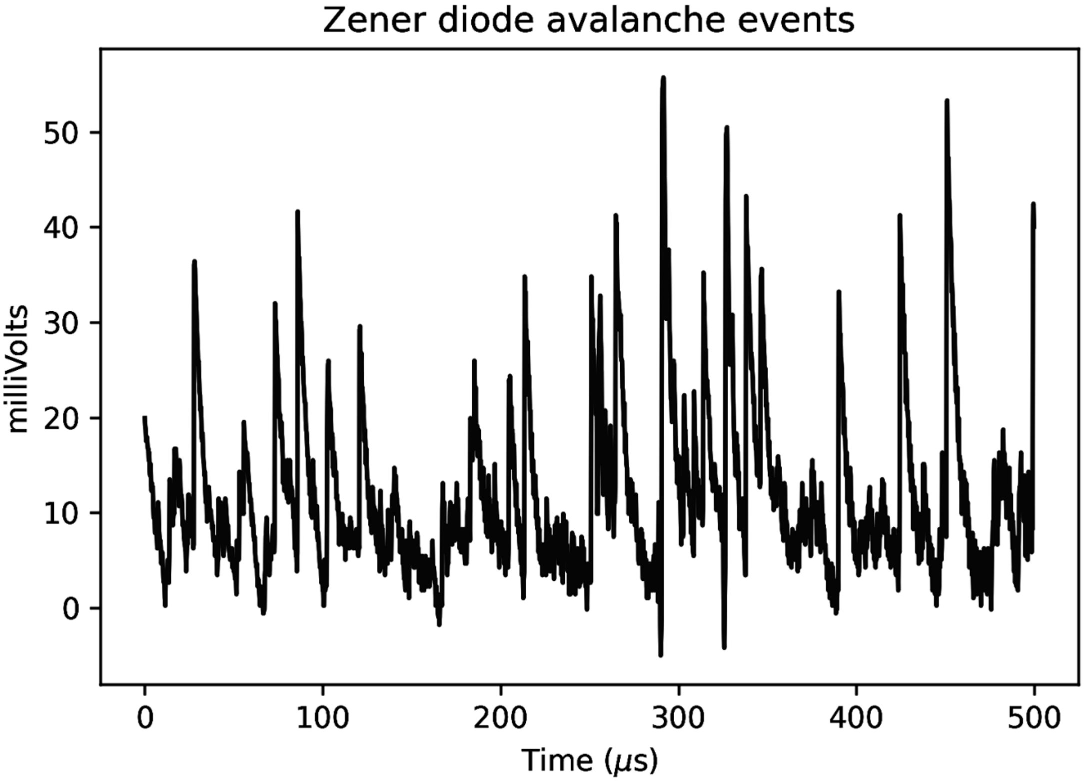

Figure 2. Avalanche events as seen by monitoring the voltage across the resistor in figure 1, with 11.9 V applied across the Zener-resistor series.

which may be directly interfaced to a digital input on the Arduino.

We next load the Arduino with the sketch shown in figure 4. This sketch uses hardware interrupts on the Arduino to watch digital input 3 for the rising edge of a square pulse coming in from the LM311. When such an edge is seen, a count variable is incremented. This watching-and-counting process is repeated for 100 ms, at which time the 'counts per 100 ms' is displayed on the Arduino's serial console (which may be copied and pasted into data analysis software).

4. Circuit discussion

A few tips on building and operating the circuit (ours is shown in figure 5, with wiring routing discussed in the caption). First, the Zener's behaviour is temperature dependent. Thus, our operational circuit has the Zener diode immersed in thermal compound, and clamped to a piece of brass, as shown in figure 6. The average counts will noticeably drift without at least some thermal control. One does not need to maintain any *particular* temperature, just a *constant* temperature, which the brass can ensure for a short periods of time [5].

Second, when testing the circuit, you can *hear* the spikes by replacing the 1 K resistor between +5 V and pin 7 on the LM311 with a small speaker. When you arrive at the avalanche voltage, you will hear a hissing sound [6].

Lastly, the Arduino's CPU can be interrupted at its fastest about once every 2.6 μs. This means we would not expect reliable counts that arrive any faster that about 390 000 per second (=1/2.6 μs), or about 39 000 in 100 ms. In practice, we should keep the pulse rate from the circuit well below this number. The count rate is strongly dependent on the applied voltage across the Zener-resistor pair. Very small

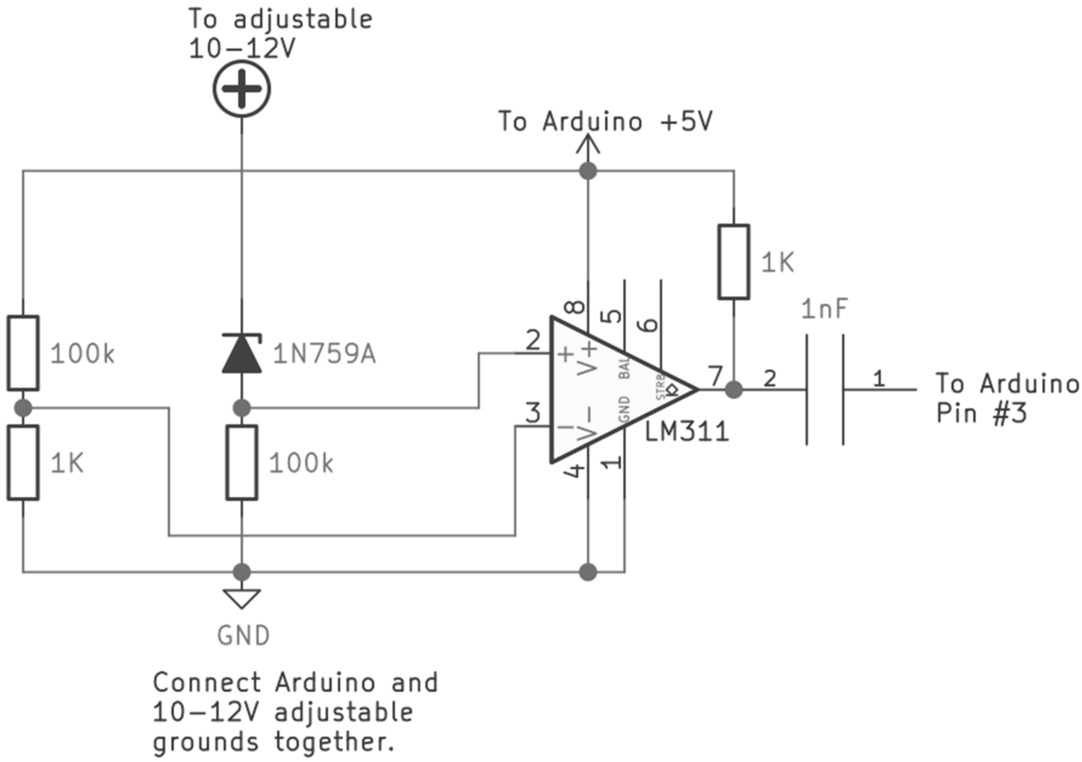

Figure 3. Circuit that uses the LM311 comparator to convert the Zener diode avalanche events shown in figure 2 into +5 V TTL pulses, suitable for input into a digital input on the Arduino. Pins 5 and 6 on the LM311 are left unconnected.

changes to this voltage (∼0.01 V) will drastically change the average count rate. Our circuit produced around 700 counts/100 ms or 7000 counts per second. The first 10 counts/100 ms were: 709, 698, 675, 711, 674, 690, 669, 652, 704, and 719.

5. Data analysis

We now run data generated by the circuit through three analysis procedures typically done with gamma-ray counting experiments. This is presented to demonstrate the statistical properties available by the Zener-generated data. These properties are consistent with a curriculum in error analysis described by Taylor [2].

The outcomes of this analysis are important, since this work claims to reproduce statistics similar to those found in gamma-ray counting experiments. We briefly summarize the salient points before continuing.

The counts/100 ms taken from the Arduino's serial console will be a (long) list of numbers. The task is to find some meaning in them. Students might be asked to find the average and standard deviation of the list, but stopping there would be premature. One might ask if there is any structure or trend in the data that these preliminary calculation might miss. This naturally leads to the construction of a histogram. As shown below this will lead to a Gaussian or 'bell shaped' distribution, which may serve as an epiphany moment for students: a circuit they constructed themselves, produces the (likely) most famous distribution of them all.

From a statistics standpoint, it is also important that the Gaussian distribution of these numbers pass statistical tests confirming the bias of the distribution to behave as such. We choose the chi-squared test here, since it is presented by Taylor [2]. Chi-squared is a test to justify how well a curve-fit (theory, in this case the Gaussian)

```
#define PIN 3

long count;
long tstart;
void setup()
{
  pinMode(PIN,INPUT);
  attachInterrupt(digitalPinToInterrupt(PIN), edge_here, RISING);
  Serial.begin(9600);
  tstart = millis();
}

void edge_here()
{
  count++;
}

void loop()
{
  long t0;

  t0 = millis();
  count = 0;
  while(millis() - t0 < 100);
  Serial.print((millis() - tstart)/1000.0);
  Serial.print(",");
  Serial.println(count);
}
```

Figure 4. Arduino sketch that will display the number of avalanche events per 100 ms to the serial console.

matches data (the histogram). Its result may be interpreted in a straightforward manner: to an observer critiquing the work, the chi-squared percentage is the chance that if the experiment was repeated, the theory/data match would be *worse*. (The observer is now left to judge the believability for themselves.)

As in gamma-ray counting, we are able to demonstrate three distributions from the Zener circuit, and justify them with the chi-squared test: the Gaussian, the Poisson, and a negative exponential.

5.1. Gaussian distribution from a histogram of incoming counts

We acquired about 1000 counts/100 ms data points. A histogram of these counts is shown in figure 7 along with a three-parameter curve fit of the form $Ae^{-B(x-C)^2}$, giving a reduced chi-squared of 1.58 [2]. This justifies the Gaussian nature of the Zener count rate to the 21% level.

5.2. Poisson distribution

As mentioned, the count rate is strongly dependent on the voltage applied to the Zener diode. If the voltage is decreased to produce a small average number of counts (for example, less than 5/100 ms), the counts should show a Poisson distribution. (This is also commonly done with gamma-ray counting experiments by setting a very restrictive discriminator level for the counter.) Here, we lowered the applied voltage to produce an average count rate of about 3 counts/100 ms, and obtained the histogram shown

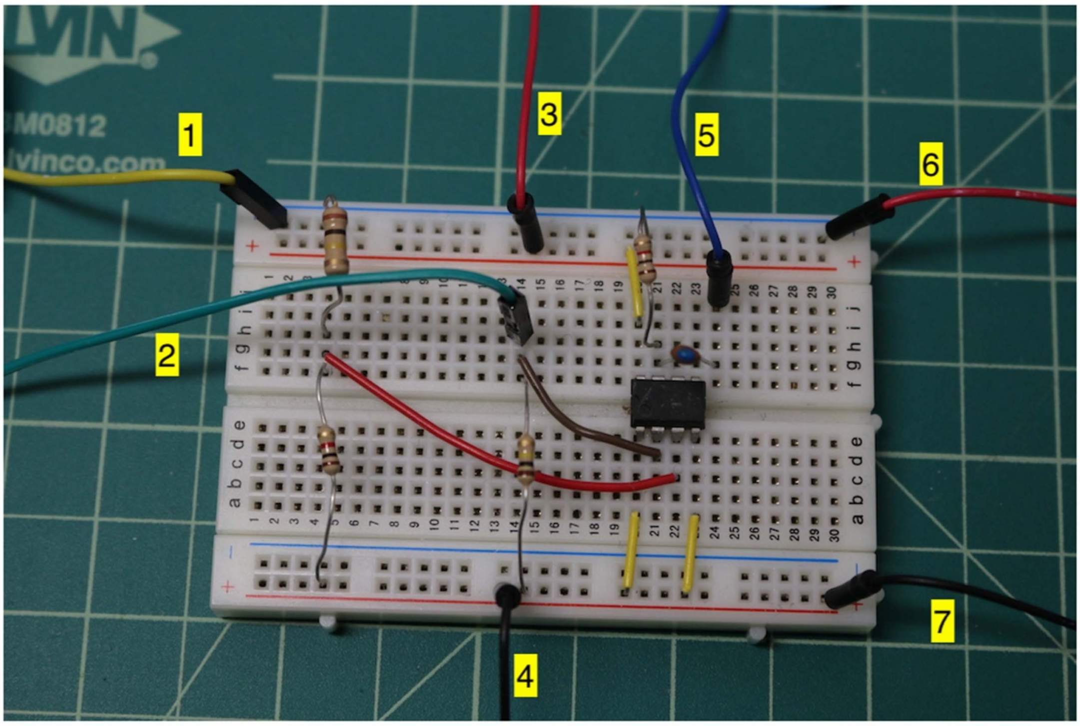

Figure 5. Our assembled circuit. Wires are as follows: 1 and 2 connect to the Zener diode; 3 to the Arduino +5 and 4 to the Arduino ground; 5 to the Arduino pin 3; 6 to the 10–12 V adjustable power supply; 7 to the ground of the adjustable power supply.

in figure 8, along with a two-parameter curve fit of the form $Ae^{-B}B^x/x!$, giving a reduced chi-squared of 0.76. This justifies the Poisson distribution of the low count rate data to the 70% level.

5.3. Pulse interval timing

By changing only the Arduino sketch to that shown in figure 9, the Arduino will display the time intervals observed between successive Zener events (the applied voltage was the same as that for the data in A above). The distribution of time intervals is shown in figure 10, which is clearly a negative exponential.

The count rate having a Poisson distribution (or Gaussian at a higher average counts) and a negative exponential distribution in interval times are related in two ways. First, the centroid from the Gaussian fit was $C = 725$ counts/100 ms, or 7250 counts/second, which compares favourably with the fit parameter in the exponential ($B = 7.79 \times 10^{-3}$ μs^{-1}) or 7790 counts s^{-1}. (The two parameters are inverses of one another.)

The second is statistical in nature [7]. The Poisson distribution is $P_\mu(\nu) = e^{-\mu}\mu^\nu/\nu!$ with μ being the average counts and ν the independent variable [2]. Suppose an experiment (such as this one) yields λ events per unit time. There will be on average λt events in some time t, described by setting $\mu = \lambda t$, giving $P_{\lambda t}(\nu) = e^{-\lambda t}(\lambda t)^\nu/\nu!$. The probability of waiting some time t and *not* seeing an event is $P_{\lambda t}(0) = e^{-\lambda t}$, meaning the probability of seeing an event is $F_\lambda(t) = 1 - e^{-\lambda t}$. The probability density function $f(t) = dF_\lambda/dt$, or $f(t) = \lambda e^{-\lambda t}$, which is what we measure (note the units of events/time), is a negative exponential. Thus, if the Poisson describes the expected count rate, the negative exponential describes the

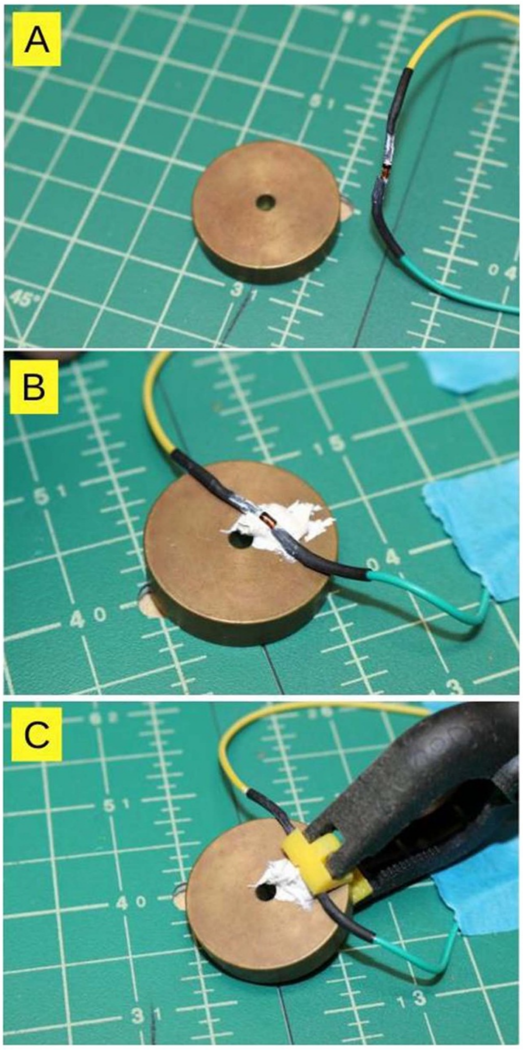

Figure 6. (A) The Zener diode near a suitable piece of brass for temperature stabilization. (B) The diode inserted into thermal compound. (C) The diode clamped as discussed in the text.

expected time between counts, which our data confirms.

A two-parameter curve fit of a negative exponential of the form Ae^{-Bx} to the distribution in figure 10 gives a reduced chi-squared of 2.36. This justifies the exponential nature of the time interval distribution to the 7.6% level.

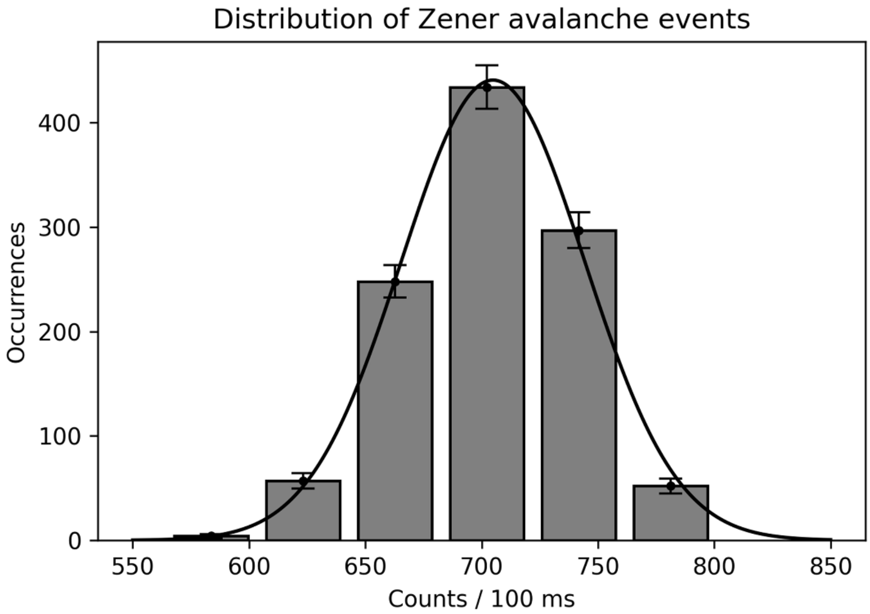

Figure 7. Distribution of Zener avalanche events (bars) and curve fit to a normal distribution (smooth curve).

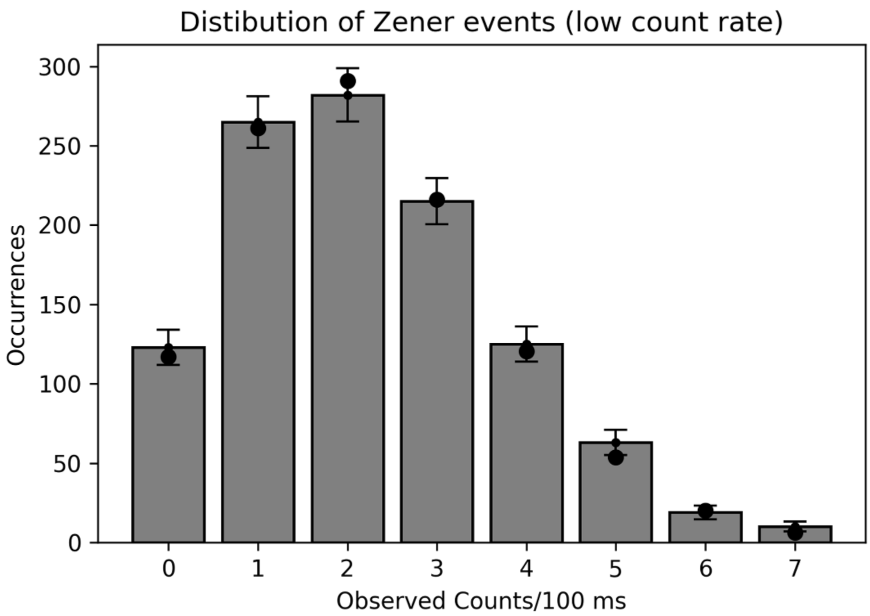

Figure 8. Distribution of Zener avalanche events (bars) for a low count rate, and curve fit to a Poisson distribution (dots).

```
#define PIN 3
#define START 1
#define END 2

#define LEN 100
unsigned int list[LEN];
int count;

int status;
unsigned long edge_time;

void setup()
{
  pinMode(PIN,INPUT);
  attachInterrupt(digitalPinToInterrupt(PIN), edge_here, RISING);
  status = START;
  count = 0;
  Serial.begin(9600);
}

void edge_here()
{
  if (status == START)
  {
    status = END;
    edge_time = micros();
  }
  else if (status == END)
  {
    status = START;
    if (count < LEN)
    {
      list[count] = micros() - edge_time;
      count++;
    }
  }
}

void loop()
{
  int i;

  if (count)
  {
    for(i=0;i<count;i++)
      Serial.println(list[i]);
     count = 0;
  }
}
```

Figure 9. Arduino sketch to perform pulse interval timing.

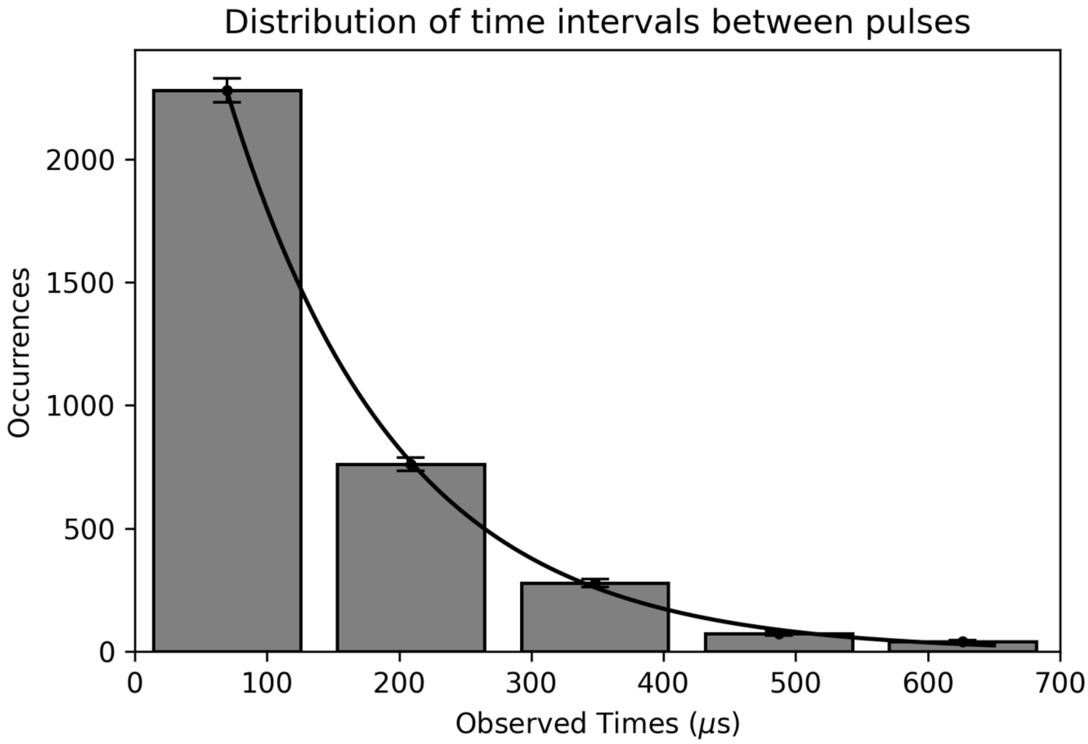

Figure 10. Distribution of time intervals (bars) between Zener diode events, with a negative exponential curve fit (smooth curve).

6. Conclusions

We have shown how a straightforward and inexpensive circuit can be used to produce data that has the same statistical properties as that acquired in gamma-ray counting experiments. It has the advantage of being a circuit students can construct themselves, even at home [8]. It has helped us deliver a lab experience in a ‘remote learning’ (i.e. learn from home) scenario, with all of the data analysis needs and statistical results found in gamma-ray counting experiments. The circuit may be used to experimentally follow lessons in error analysis from Taylor [2], in cases where gamma-ray counting equipment is not available.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors. (www.dropbox.com/s/bu95yaelw0ldd1u/tbensky_pic_and_bio.docx?dl=0)

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[2] Taylor J R 1997 *An Introduction to Error Analysis* 2nd edn (Mill Valley, CA: University Science Books) chs 5 and 12

[3] Lampert B *et al* 2016 Robust, low-cost, auditable random number generation for embedded system security *SenSys ‘16: Proc. 14th ACM Conf. on Embedded Network Sensor Systems* (*November 2016*)

[4] ON Semiconductor 1N759A (Available at: Digikey.com www.digikey.com/en/products/detail/on-semiconductor/1N759A/977705) (Accessed 11 01 2021)
[5] Other metallic objects are perfectly suitable. During at "at home" running of this lab, our students have used a wrench, section of copper pipe, CPU cooling fins for example (all without thermal compound). All suitably stabilized the Zener avalanche counts. Silver paste is not recommended, since it conducts and may result in a short circuit around the diode
[6] Bensky T (Available at: https://youtu.be/PKsEFBwK4GU) (Accessed 11 January 2021)
[7] Cooper J C B 2005 The Poisson and exponential distributions *Applied Probability Trust* (available at: https://stats.stackexchange.com/questions/2092/relationship-between-poisson-and-exponential-distribution) Includes a lively discussion on the relationship between the Poisson and exponential distributions (Accessed 15 February 2021)
[8] The adjustable voltage for the Zener can be delivered using the wiper of a (10k) potentiometer connected across 18V made by two 9V batteries in series

Tom Bensky is a professor at Cal Poly, in San Luis Obispo, CA (USA). He teaches a variety of classes, from introductory astronomy to advanced labs to the"history of navigational science." He enjoys designing and building electronic circuits that produce data to drive student data-analysis exercises.