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8.13-14 Experimental Physics I & II "Junior Lab"
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Poisson Statistics

MIT Department of Physics

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In this experiment you will explore the statistics of random, independent events in physical measurements. The random events used in this study will be pulses from a scintillation detector exposed to gamma rays from a radioactive source. The measurement will be compared to Poisson or Gaussian distributions which often govern the spread of physical data. A computer simulation using Monte-Carlo techniques will provide comparison for different numbers of events and give a demonstration of “normal” statistical fluctuations. This comparison technique is widely used in modern physics.

1. PREPARATORY QUESTIONS

1. Describe how a scintillation counter works, starting from the entrance of an energetic charged particle or photon, and ending with an electrical pulse at the output of the photomultiplier. Why are subsequent signals independent?
2. Suppose the mean counting rate of a certain detector of random events is 2.1 counts per second. What is the probability of obtaining zero counts in a one-second counting interval? What is the most likely interval between successive pulses?
3. Given the formula for the Poisson distribution (Equation 2), prove each of the following:
 - $\langle x \rangle = \mu$
 - $\langle x^2 \rangle = \mu(\mu + 1)$
 - $\langle (x - \mu)^2 \rangle = \mu$

where $\langle x \rangle$ signifies the mean value of x .

4. Plot the frequency distribution of counts when the average counts per interval is 1.5.
5. Puzzler: Some experiments have painfully slow counting rates that try the experimenter’s soul and make him or her question the performance of even the most reliable equipment. Suppose you are running an experiment that yields no counts in 11 hours and two counts in the 12th hour. Give a quantitative answer to the question: what is the likelihood that the equipment is malfunctioning?

2. THEORY OF POISSON STATISTICS

A sequence of independent random events is one in which the occurrence of any event has no effect on the occurrence of any other. One example is simple radioactive decay such as the emission of 663 KeV photons by a sample of ^{137}Cs . In contrast, the fissions of nuclei in a critical mass of ^{235}U are correlated events in a “chain reaction” in which the outcome of each event, the number of neutrons released, affects the outcome of subsequent events.

A continuous random process is said to be “steady state with mean rate μ ” if

$$\lim_{T \rightarrow \infty} \left(\frac{X}{T} \right) = \mu \quad (1)$$

where X is the number of events accumulated in time T .

How can one judge whether a certain process does, indeed, have a rate that is steady on time scales of the experiment itself? The only way is to make repeated measurements of the number of counts x_i in time intervals t_i and determine whether there is a trend in the successive values of x_i/t_i . Since these ratios are certain to fluctuate, the question arises as to whether the observed fluctuations are within reasonable bounds for a fixed rate. Clearly, one needs to know the probability distribution of the numbers of counts in a fixed interval of time if the process does indeed have a steady rate. That distribution is known as the Poisson distribution and is defined by the equation:

$$P(x; \mu) = \frac{\mu^x e^{-\mu}}{x!} \quad (2)$$

which is the probability of recording x counts (always an integer) when μ (generally not an integer) is the expected number, the mean rate times the counting time interval. It is easy to show that the standard deviation of the Poisson distribution is simply $\sqrt{\mu}$, that is, the square root of the mean. Derivations of the Poisson distribution and its standard deviation are given in References [1, 2]. You should study and understand Binomial, Poisson and Gaussian distributions and their limits of application.

3. EXPERIMENT

In the first part of this experiment you will set up a scintillation counter, expose it to gamma rays from a radioactive source (and the ubiquitous cosmic rays), and record the frequency distribution of the numbers of counts in equal intervals of time. This will be repeated for four situations with widely different mean count rates, approximately 1, 5, 10, and 100 counts per second. The “real” average rate you know only at the end but you should aim for these values within 25%. The experimental distributions and their standard deviations will

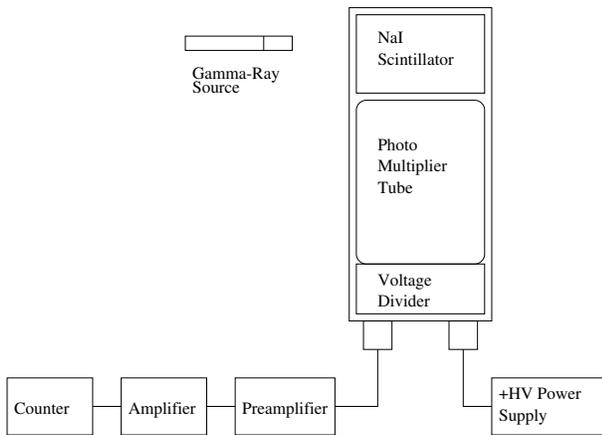


FIG. 1: The setup for measuring the number of counts from a random process (radioactive decay) in a given time interval. An oscilloscope (not shown) is used to monitor the proper functioning of the system.

be compared with the theoretical distributions and their standard deviations.

Later, you will generate Poisson distributions by Monte Carlo simulations on a Junior Lab PC and will also compare them with the ones produced by nature in your counting measurements.

3.1. Setup to Measure Poisson Statistics

Set up the scintillation counter as shown in Figure 1. Expose the detector to the gamma rays from a ^{137}Cs or ^{60}Co laboratory calibration source (a $1/2'' \times 5''$ plastic rod with the source embedded in the colored end). The voltage applied to the photomultiplier should be $\approx +1000$ volts. The output of the photomultiplier is fed to the “INPUT” connector on charge-sensitive preamplifier. Use the oscilloscope to record the voltage waveform taken from the output of the preamplifier and draw it in your lab notebook. Note especially the rise and decay time of the signal as well as the peak amplitude and polarity.

The output of the preamplifier is then connected to the “INPUT” (connector on the back or front of the amplifier). The amplified signal should be taken from the “UNIPOLAR OUT” connector on the front of the amplifier, and fed to the “POS IN(A)” connector on the scaler. Set the amplifier to have a moderate gain and for positive pulses. Start with the scaler’s discriminator set at its lowest value (0.1V). Set the scaler to repeatedly acquire for 5 seconds, display the result and then start again.

Note: Throughout Junior Lab, you should pay close attention to the polarities of applied and detected voltages. Incorrectly setting the polarity on an oscilloscope trigger can be very frustrating!

3.2. Procedure

Examine the output of the amplifier on the oscilloscope (sweep speed $\sim 1\mu\text{sec}/\text{cm}$, vertical amplitude ~ 1 volt/cm) to confirm the proper performance of the measurement chain. Adjust the gain of the amplifier to produce signal pulses of $\sim +3$ volts. If you trigger the scope on the “rising edge” of the pulses and set the trigger level to $\sim +3$ volts, you should see a signal which starts on the left-hand side of the scope display at ~ 3 volts, rises to a maximum of about ~ 5 volts, goes negative and finally levels off at zero. If you also set the discriminator on the counter to 3 volts, there should be an approximate one-to-one correspondence between pulses counted and pulses displayed. Ask for assistance on this step if you are unfamiliar with the operation of an oscilloscope.

Incidentally, even without a “check source” nearby, you should see signals due to “cosmic-rays” at the rate of $\approx 1 \text{ cm}^{-2} \text{ min}^{-1}$.

You can control the counting rate by adjusting the distance of the source from the scintillator, by varying the high voltage supplied to the photomultiplier, varying the gain of the amplifier, or changing the threshold level of the discriminator. Arrange things to yield four different mean count rates of approximately 1 sec^{-1} , 4 sec^{-1} , 10 sec^{-1} , and 100 sec^{-1} .

Record your instrumental settings and prepare tables in your lab notebook for recording the count data in neat and compact form.

At each of these approximate rates, record the counts for $j_{\text{max}} = 100$ repeated one-second intervals directly into your lab notebook. For each of the four settings, record the number of events in one consecutive run of 100 seconds as well.

3.3. Analysis

The following analysis requires the use of repetitive arithmetic on the collected data set. You could use either Matlab or any other preferred tool on the MIT Server.

- For each of the four runs calculate and plot the cumulative average, $r_c(j)$, of the rate as a function of the sequence number, j , of the count. By “cumulative average” is meant the quantity

$$r_c(j) = \frac{\sum_{i=1}^{i=j} x_i}{\sum_{i=1}^{i=j} t_i} \quad (3)$$

where x_i is the number of counts detected in time t_i . For a process which is truly steady with mean rate μ , $r_c(j)$ should converge to μ in the asymptotic limit. Include error bars to demonstrate convergence.

- Calculate the mean and standard deviation of each of the four 100-trial distributions and compare to

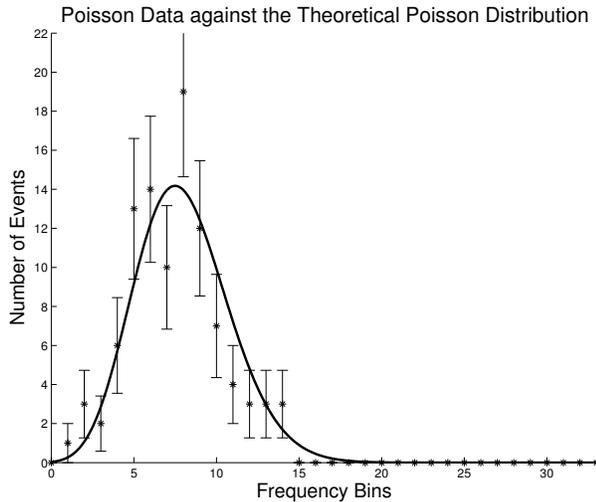


FIG. 2: A frequency distribution of observed numbers of counts. The renormalized Poisson distribution for the observed mean value is also plotted.

your own measurements. Make a plot of the “number of counts” on the horizontal axis and data points for the “frequency” of occurrence for each bin on the vertical axis. Be sure to include error bars.

- c) Plot the data with errors as in Figure 2 and using the mean rate just determined, calculate the Poisson frequency distribution (renormalized by multiplying by the total number of readings). Plot both distributions on the same axes for ease of comparison.
- d) For the observed distribution with the lowest mean rate, take the highest deviation from that mean and test whether you might be justified in concluding that the counter was malfunctioning. Remember that there were 100 opportunities for such a deviation to occur.
- e) For large values of μ you can use the Gaussian approximation to the Poisson formula as given by the relation

$$\lim_{\mu \rightarrow \infty} p(x; \mu) = \frac{1}{\sqrt{2\pi\mu}} e^{-(x-\mu)^2/2\mu}. \quad (4)$$

Compare the Poisson and Gaussian distributions for $\mu = 4$ and 10.

3.4. Simulating Poisson Statistics Using Matlab

On the MIT Server, add the Junior Lab Locker by typing

```
%> setup 8.13
```

Within Matlab type

```
>>addpath /mit/8.13/matlab
```

There are two Matlab scripts entitled `poisson.m` and `poissonsimsim.m`. For information on how to use either one, type `help poissonsimsim` from within Matlab. For example type `poissonsimsim(3,20)` which will generate a 20 sample population with a mean of 3. The solid curve represents the theoretical poisson distribution while the red dots represent the simulated sample population. The `poissonsimsim` function will output two vectors: the frequency of each rate (i.e. the counts in each bin shown in the graph) and the count rates for all of the trials.

The following instructions apply to either method.

1. Generate 1000-trial distributions for your MEASURED mean rates ($\approx 1, 4, 10, 1000$).
2. Next, generate ten 100-trial distributions for each of the four mean counts you obtained in the experimental section using the scintillation counters. Record the mean values and standard deviations for each set of 10 distributions.
3. Compare the Monte Carlo-generated Poisson distributions with the experimental ones you obtained with the scintillation counter. The mean of the standard deviations should converge (within some statistical error) to the square root of the mean that is input to the Poisson generator.
4. Determine the error on μ and σ from the scatter of the ten distributions.

4. STATISTICAL EXERCISE

1. For the hundred one second measurements at ≈ 4 Hz, evaluate the average and the variance and compare the results with the mean and standard deviation of the long 100 second run. Are they consistent?
2. Plot the distributions of your measured data sets and compare to Poisson distributions of your experimental means. Are the variances in agreement with the theoretical expectation?
3. Fit the ≈ 4 Hz data set to both gaussian and poisson functions. Which is preferred? At what confidence level?

5. SUGGESTED THEORETICAL TOPICS FOR ORAL EXAM

1. The Poisson distribution, its origin from the binomial distribution and the limits of its application.
2. The Gaussian approximation to the Poisson distribution $P(x; \mu)$ for $x \gg 10$.

3. The differential distribution in the time lag between successive random pulses that occur at a fixed average rate.

[1] P. Bevington and D. Robinson, *Data Reduction and Error Analysis for the Physical Sciences* (McGraw-Hill, 2003), 3rd ed.
 [2] A. Melissinos and J. Napolitano, *Experiments in Modern Physics* (Academic Press, 2003), 3rd ed.

APPENDIX A: MONTE CARLO GENERATION OF A RANDOM VARIABLE

Suppose we have a source of random numbers with a uniform distribution from 0 to 1. If we represent the uniform distribution by $q(y)$, so that $q(y')dy'$ is the probability that the random number y lies between y' and $y' + dy'$, then obviously $q(y') = 1$. The problem is how to convert a given random number y from this uniform distribution into a random variable x with a specified distribution $p(x')$ such that $p(x')dx'$ is the probability that the variable x will turn up with a value in the infinitesimal interval between x' and $x' + dx'$. We must find a relation between the distributions of y and x such that $p(x')dx' = q(y')dy' = dy'$.

To do this we compute, analytically if possible but otherwise numerically, the integral

$$P(x) = \int_{-\infty}^x p(x')dx' \tag{A1}$$

which is the probability that the random variable will turn up with a value in the interval between $-\infty$ and x . From this definition it follows that

$$\lim_{x \rightarrow \infty} P(x) = 1 \tag{A2}$$

since the probability that the random variable will turn up with some value is unity. Given the random number y , we set $y = P(x)$ and solve for x . To find the distribution of the resulting value of x we differentiate this expression, using the rule for differentiating a definite integral with respect to its upper limit, and obtain $dy = dP(x) = p(x)dx$. Thus the distribution of x selected in this way is identical to the one specified.

Figure 3 shows how this works graphically. From the figure it is evident that a horizontal line at a random position y_i on the y -axis is more likely to intersect the

$P(x)$ function where it is steeper than elsewhere; i.e., where the differential probability is larger than elsewhere.

The Poisson probability, being a discontinuous function, is handled in a similar way, but with a summation rather than an integral. Given a value of $\mu < 88$ and a

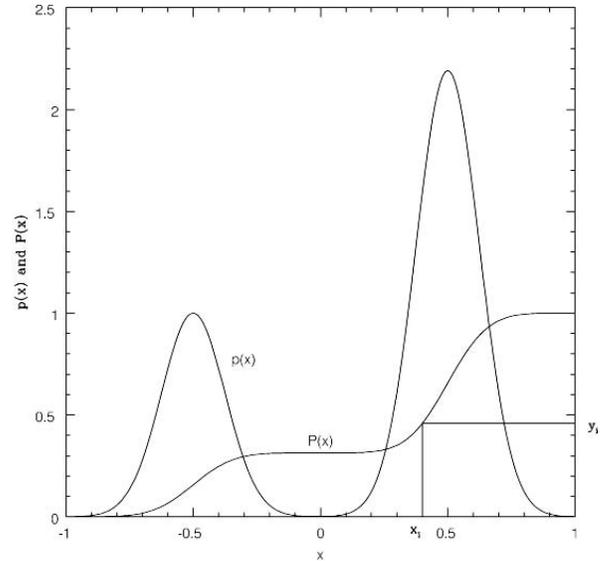


FIG. 3: Illustration of Monte Carlo selection of a random variable with a specified differential probability distribution is shown above. y_i is a random number between 0 and 1. x_i is the value of the variable for which the integral probability distribution equals y_i .

random number y , the Poisson Simulator find the smallest value of x for which $P(x; \mu) > y$, where P is defined by the formula

$$P(x; \mu) = \sum_{x'=0}^{x'=x} p(x'; \mu) \tag{A3}$$

in which $p(x'; \mu)$ is the Poisson probability specified above. That value of x is the desired Poisson variate.

Inspect the Matlab `.m` files where the algorithm is described in more detail.