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Experiments on Radioactivity in a Student Laboratory

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Abstract: This paper shows how to run some experiments on radioactivity in a student laboratory, aiming to investigate the Poisson distribution of decays and the use of chi-squared test. Avoiding specific problems of safety control, which is necessary when radioactive sources are used, we are proposing measurements of the natural background and emission of potassium chloride. The detector is a Geiger-Müller tube. In the case the budget for laboratory and its equipment is limited, the use of a virtual alternative is proposed. Some virtual experiments are discussed too.

Keywords: Laboratory, Physics Class, Radioactivity, Poisson Distribution

1. Introduction

This paper is proposing an experiment on radioactivity suitable for a student laboratory, which does not require any safety control, because it is investigating the natural background and the radioactivity of potassium chloride, a salt with a very low emission. Let us point out that the use of sealed radioactive sources, even those low-risk for a student laboratory, requires some specific safety and security criteria and controls. Since the aim of this experiment is not only the measurement of radioactivity, but also the study of Poisson distribution and application of chi-squared test, this can be done in complete safety with the normal environmental radioactivity [1].

In physics and other sciences, we often use the Gaussian distribution. However, we have to remember that not all natural processes are following it: in fact, the radioactive decays are governed by the Poisson distribution. This distribution is named after the French mathematician Siméon Denis Poisson and is good for radioactive decay [2], telephone calls [3] and requests for documents on web servers [4] and many other phenomena. The Poisson distribution is also known as the law of rare events, where the word 'law' is used as a synonym of probability distribution [5]. The name may be misleading, because the total count of occurrences in a Poisson process needs not be small. For instance, in the case of a radioactive source, the number of decays in a certain time interval seems large, but, since decaying nuclei are rare when compared with Avogadro number of atoms, the occurrences are following a Poisson distribution.

In this paper, we will see the experiments using a Geiger-Müller tube. After, we will discuss the use of a virtual instrument, simulating it, for some

experiments. This virtual alternative is quite interesting, especially when the laboratory budget is limited, and only a few real instruments can be operating in it.

2. Experiments in a real laboratory

During the experiments in a real student laboratory we can use, for instance, the Geiger-Müller tubes and timers with integral power supply distributed by PASCO. These tubes sense beta, gamma and alpha radiations. The built-in power supply allows a direct connection to the tube and an easy use of it in the laboratory. The tube is connected with PASCO Smart Timer.

The Geiger-Müller detector is a tool able to detect radioactive decays in the environment. Depending on the emission, the decay produces a particle (alpha or beta) or a photon (gamma) that entering the tube is able to produce an electrical discharge in the gas contained inside. The sealed gas is placed between two electrodes, one at high voltage, and the other to ground. Each time a high energy particle enters the tube filled with gas, this is ionized, and the high voltage causes an electric discharge. The detector is connected to a Smart Timer stopwatch counter, recording the discharges produced in the tube in a chosen time period, for instance of 30 seconds. Longer periods can be chosen too. The Smart Timer gives an audible signal when the count is incremented. In the experiment, a reading is then the counts of discharges in a time interval of 30 seconds.

At first, hundred readings can be recorded relative to the background radiation of the environment. The Geiger-Müller is resting on the table, free from constraints, at a suitable distance from ionizing sources. It is also useful the students know about the



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possibility that their wrist watches could be radioactive. In fact, some old watches have the dials with luminous paints, that until the 60ties, were containing Radium or Promethium. These kinds of watches are no longer manufactured today. There is no risk for the person wearing the watch, but, if the student had it on, this is affecting the background. After that of the background, another set of a hundred readings is obtained using the salt. The Geiger detector is suitably placed in a flask containing 1 kg of potassium chloride, taking care that the instrument is not in contact with the salt itself. After collecting these data, the student can prepare plots of the frequencies of counts, such as those in the Figure 1. Note that the radioactivity of KCl is very low.

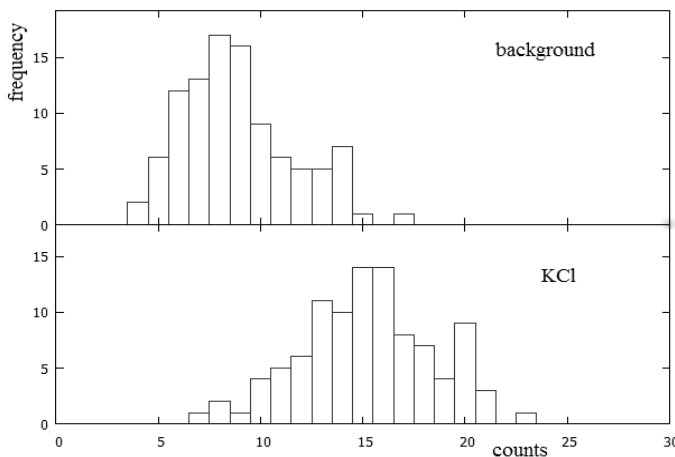


Figure 1 – Frequencies of the counts of background and KCl.

Further calculations can be obtained using a Microsoft Office or Apache OpenOffice worksheet. Apache OpenOffice is an open-source software suite, which contains a word processor (Writer), a spreadsheet (Calc), a presentation application (Impress), a drawing application (Draw), a formula editor (Math), and a database management application (Base) [6]. Using Calc, we can obtain the mean value M of the counts and the variance V . For the data in Figure 1, we have $M=8.92$, $V=7.63$ for the background, and $M=15.20$, $V=10.63$ for KCl.

3. Further data analysis

After the experimental data acquisition of background radiation and salt, and the previously discussed preliminary evaluations of the frequency of counts and their mean values and variance, we can investigate the fact the experimental frequency is following the Poisson law. Choosing an appropriate grouping, we can split the sample into a number of classes, between 5 and 15. Let us remember that the classes must be mutually exclusive, so that no data value can fall into two different classes, but all data values must be included. The classes must be continuous, so that there are no gaps in a frequency distribution. The classes must be equal in width: the exceptions can be the first or last class. An example

of grouping in classes of the observed occurrences is given in the Figure 2. There, we can see the experimental occurrences compared with the expected Poisson values. The plot and the theoretical values are given by the worksheet [7].

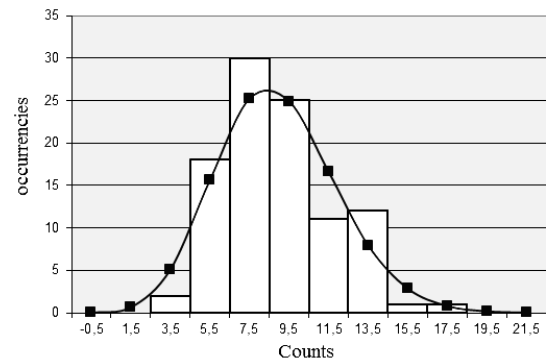


Figure 2 – An example of grouping in classes of the background radioactivity compared with the Poisson expected values.

After the grouping in classes and the corresponding frequencies, we can determine whether the distribution assumes a Poisson trend or not, using the chi-squared test. The Poisson probability of occurrence is given according the formula:

$$P(n) = e^{-M} \frac{M^n}{n!} \quad (1)$$

In (1), M is the mean value and n the number of occurrences.

This probability is compared with experimental frequencies of the grouped data, by means of the Pearson's chi-squared test [8]. This is the best-known of many chi-squared tests, which are statistical procedures whose results are evaluated by reference to the chi-squared distribution, investigated by Karl Pearson in 1900 [8]. The Pearson's chi-squared test works on a null hypothesis stating that the frequency distribution of certain events observed in a sample is consistent with a particular theoretical distribution [8]. The events considered must be mutually exclusive and have total probability 1. The value of the test-statistics is given by:

$$\chi^2 = \sum_{i=1}^c \frac{(N_{observed,i} - N_{theor,i})^2}{N_{theor,i}} \quad (2)$$

In (2), c is the number of non-empty classes, and N the number of observed and theoretical (expected) occurrences in each class. For the chi-squared test, we can use worksheets [7].

In the laboratory then, the student can observe the natural radioactivity, use an instrument and apply some statistics. Approximately four hours are necessary to run experiment and data analysis.

4. A virtual alternative

In the case the budget does not allow a complete equipment of the laboratory, with several Geiger tubes and smart timers, it is possible to use a virtual alternative. Even the whole laboratory can be replaced with a virtual one. Such a laboratory is a Web page, equipped with virtual objects and tools simulating the real ones. The example we show here is concerning a laboratory for radioactivity developed at the California State Polytechnic University. Entering the virtual rooms of the “Cal Poly Physics Department's Virtual Radiation Laboratory” [9] and “Applets Java” [10], the students can find detectors and radioactive sources for experiments. This virtual laboratory was created by Peter Siegel, who remarks this was made with the purpose to give the students “an introduction to radiation detection and data analysis without being radiated”. In the Web pages [9] and [10], we can find the simulation of four different detectors: a Geiger counter, two gamma detectors and a liquid scintillation detector. The Java Applet Geiger Counter was created by Andres Cardenas, of the California Polytechnic University too [11].

Web sites [9-11] are displayed with the internet browsers and instruments are simulated by Java Applets. Let us remember that Java is an object-oriented programming language, enabling the creation of suitable applications to be implemented in many environments. In particular, when an application written in Java is installed inside a browser (Chrome, Mozilla, Explorer), it is called a Java Applet. In [11], we can run several experiments. Among them, we can imagine the evaluation of half-life of a radioactive material, for instance, or study the distribution of radioactive decay (in the Figure 3 we can see how the instrument appears in the Web page). The simulator can also determine a characteristic of the Geiger counters, its dead time. As previously told, a radioactive decay causes a discharge of the counter; this discharge takes some time, during which the instrument is not able to measure any other decay: this is called the dead time of the instrument, τ .



Figure 3 - Screenshot of the virtual laboratory of radioactivity [11], equipped with a Geiger counter and two sample holders. These holders can be left empty to measure the natural background, or loaded with two different types of radioactive sources.

The virtual Geiger counter has two sample holders where it is possible to put inside two types of radioactive sources. The simulated samples are radionuclides Ba137m and Mn-54 (5 micro-curies) [12]. The sample holder can also be left empty, and thus the simulator measures the radioactivity of natural background. A possible experiment is then the study of the natural background. Another possible virtual experiment with applet [11] is the determination of the half-life of Ba137m (half-life of about 2.55 minutes). First of all, let us see in details the determination of the dead time of this instrument.

5. Measurement of the dead-time

A Geiger tube is a gas-filled radiation detector. It usually takes the form of a cylindrical outer shell (the cathode), with inside a sealed gas-filled space, and a central wire (the anode) held at a high voltage with respect to the cathode. The gas is generally Argon at a low pressure, with a small quantity of a quenching vapour. If a gamma particle interacts with the instrument, primarily with its walls, an energetic electron is produced that can travel through the tube. This primary electron produces ionization along its path, by collisions with the fill gas. The new electrons and the original one are accelerated, producing a cascade of ionization known as the Townsend avalanche. As a consequence, a dense sheath of ionization is created along the central wire, producing what is termed a Geiger-Müller discharge.

The intense electric field collects electrons to the anode and repels positive ions. The electrons are collected within a few microseconds, while massive positive ions are accelerated quite slowly, due to their low mobility, towards the cathode. These ions produce a positive space charge surrounding the central wire: the temporary presence of this space charge stops additional avalanches, because it is reducing the field gradient near the anode below the

avalanche threshold. As a consequence, any approaching electron does not gain enough energy to start a new avalanche. The detector is then “dead” for the time the ions migrate far enough from the inner electrode. The time required for recovery a value of the field high enough to generate a new discharge and then a new count is the “dead time” τ , which is of the order of 100 microseconds. During the dead time, the instrument is not able to measure any other decay. Let us define n as the true decay rate in a fixed time interval and R the counting rate obtained by the Geiger counter during the same time interval. It is assumed that $n = R / (1 - R\tau)$ [13].

The classic method for measuring the dead time of the Geiger counter is the so-called “method of the two sources” [13,14]. Suppose that n_1 and n_2 are the true rates of the two sources and R_1 , R_2 and R_{12} the counting rates measured for the two sources, separately and together, respectively. It must be: $n_1 + n_2 = n_{12}$. Then, we have:

$$n_1 = \frac{R_1}{1 - R_1\tau}; n_2 = \frac{R_2}{1 - R_2\tau}; n_{12} = \frac{R_{12}}{1 - R_{12}\tau} \rightarrow \frac{R_{12}}{1 - R_{12}\tau} = \frac{R_1}{1 - R_1\tau} + \frac{R_2}{1 - R_2\tau} \quad (3)$$

The dead time is:

$$\tau = \frac{R_1 R_2 - [R_1 R_2 (R_{12} - R_1)(R_{12} - R_2)]^{1/2}}{R_1 R_2 R_{12}} \quad (4)$$

If the background count rate R_b is measured too, Eq.4 turns into:

$$\tau = \frac{X [1 - (1 - Z)^{1/2}]}{Y} \quad (5)$$

In Eq.5, we have $X = R_1 R_2 - R_b R_{12}$, $Y = R_1 R_2 (R_b + R_{12}) - R_b R_{12} (R_1 + R_2)$ and $Z = Y (R_1 + R_2 - R_b - R_{12}) / X^2$.

The virtual laboratory [11] has two sample holders, and the user has the possibility to apply the method of the two sources. It is necessary to use the source Mn54 with a measurement time interval of 10 seconds, for instance. Loading a sample holder, leaving the other empty, the individual measured counting rates $R_1 = 2735$ and $R_2 = 2737$ have been obtained. Loading both the sample holders, the counting rate $R_{12} = 5073$ is obtained. From Eq.4,

$\tau = 3 \times 10^{-5}$ sec. The effect of background is negligible.

6. Counting rate statistics

In the virtual experiment, to show that the counting rate of radioactive decay has a Poisson distribution, we can use the source Mn54. The run needs approximately two hours. We can decide an observation period of 10 seconds over which the Geiger counts the decays. We repeated the reading of the counting rates for $N = 180$ times. After having obtained 180 counting rates, we grouped them in several classes, spanning the range between the minimum observed value and the maximum value of the real rate, $n_{\max} = R_{\max} / (1 - R_{\max} \tau)$. R_{\max} is the maximum value read during the experiment. Figure 4 shows the data grouped in classes and the experimental frequencies, compared with the Poisson distribution. Of course, we can also compare experimental and theoretical distributions by means of the Pearson’s chi-squared test as we did for the real data.

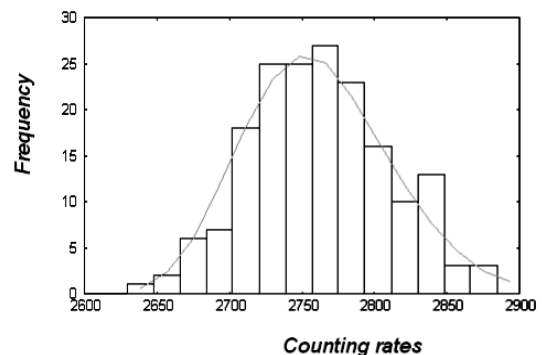


Figure 4 - Measured frequencies and Poisson distribution.

7. Squeezing out Barium

The virtual Geiger applet we used in the previous two experiments works with Barium137 too. As told in [9,10], to record counts from the Ba137m samples, it is necessary to “squeeze out” the radioactive sample. The button refreshes both sources when clicked.

To imagine what this button is simulating for, we have to note that radionuclides used in hospitals for radiotherapy, such as Technetium-99m for instance, have very short half-lives. For this reason, specific isotope generators are used. A Technetium-99m generator, or colloquially a Technetium cow or Moly-cow (Moly for Molybdenum) is a device used to extract the metastable isotope Tc99m from a source of decaying Molybdenum-99 [15]. Mo-99 has a half-life of 66 hours and can be easily moved for long distances from nuclear centres to hospitals, where its decay product, Technetium-99m, which as a half-life of only 6 hours, is extracted and used. For physics laboratories, similar small isotope generator kits of Barium-137m exist [16]. The PASCO Cs-137/Ba-137m isotope generator for instance, is one of them. Each generator kit contains Cs-137 and an eluting solution. The isotope parent Cs-137 has a half-life of 30.1 years and decays to the metastable

state of Ba-137m. This isotope further decays by gamma emission with a half-life of 2.6 min to the stable Ba-137 element. According to PASCO, during the elution, Ba-137m is "milked" from the generator, leaving behind the Cs-137 parent. The regeneration

of the Ba-137m is due to the fact that Cs-137 continues to decay. In less of one hour, the generator is ready again. 30 minutes after elution, the activity of the Ba-137m sample is reduced to a level low enough to be safe for handling.

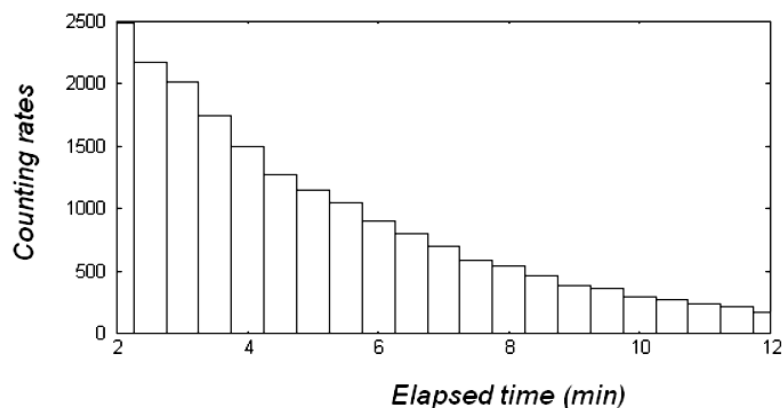


Figure 5 - Counting rates of Ba-137m showing the behaviour of the decay.

After squeezing out Ba137, we can read the decays on a time interval of 10 seconds and plot them as a function of the elapsing time. Figure 5 is showing that the counting rates are decreasing with time. From these data, we can obtain the half-life of Ba-137m.

Conclusions

The paper reports the description of some real and virtual experiences on radioactivity for a student laboratory. The real laboratory uses some PASCO equipment, whereas the virtual one is equipped by virtual instruments and sources, created with Java Applets. The experiments we discussed (determination of dead time, statistics of counting rates, half-life) and ran using the virtual instrument and sources, show that a virtual laboratory is a valid alternative to a real one.

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- [12] One of the simulated radioactive materials is Mn54. Naturally occurring manganese (Mn) is composed of one stable isotope, Mn55, and 18 radioisotopes. They have been characterized with the most stable being Mn53 with a half-life of 3.7 million years. Mn54 with a half-life of 312.3 days. The other simulated material is Ba137m. Naturally occurring barium (Ba) is a mix of six stable isotopes and one very long-lived radioactive primordial isotope, Ba130, recently identified as being unstable by geochemical means, from analysis of the presence of its daughter Xenon-130 in rocks. There are a total of twenty-two barium isotopes known, but most of these are highly radioactive with half-lives ranging from several milliseconds to several minutes. Ba137m has a half-life of 2.55 minutes. It is obtained from the decay of Caesium137 (Cs137), which is a radioactive isotope of Caesium, formed mainly as a fission product by nuclear fission. The half-life of CS137 is of about 30.1 years. Ba-137m is responsible for gamma-ray emission. The photon energy of Ba-137m is 662 keV. These photons can be useful in food irradiation and in radiotherapy.

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