Prototyping Liquid Argon Dark Matter Detector

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Abstract

The aim of the project is to build a small ion chamber serving as a prototype of a much larger dark matter detector to be built in the future. This is a brand-new project at Fermilab; my task would be to come up with the prototype ion chamber and a first set of measurements. To start with, the small chamber is going to be filled with Argon extracted from the air, i.e. predominantly 40Ar and traces of the radioactive ^{39}Ar isotope. The Argon will be in its gaseous phase when introduced in the chamber. Some properties of the inside volume are being recorded (electric field configuration, voltage output etc.). Subsequently, we will make use of Argon extracted from underground gas wells, which contains smaller concentrations of decaying ^{39}Ar. The beta-decay of ^{39}Ar must be well monitored, because it is the main background source for WIMP dark matter searches. Also, the chamber is put under high voltage by sending a current through an iron rod placed along the horizontal axis of the cylindrical chamber. After the passing of a highly energetic particle, the electric field separates the newly formed positive ions and negatively charged electrons. After data taking and analysis of this configuration, the next step consists in replacing the gaseous Argon with liquid Argon and take new data samples to be compared with the previous ones. The project combines aspects of cryogenic design, work with low-radioactivity material and data analysis. Furthermore, the CERN-software Garfield allows us to simulate the electric field configuration inside the chamber. In fact, the exact field configuration in three dimensions is not known for most drift chamber geometries. In addition, the geometry can become highly complicated locally (the shapes of the electrodes, for instance). The knowledge of the field configuration is of particular importance,

however, since only its precise knowledge allows for a proper determination of the background radiation. The next step would then be to investigate inasmuch the results and properties of the small chamber can be taken over to the original size chamber to be constructed. This will be done if time is available; my main task is to get a functioning prototype ion chamber providing us with data which should permit us to make good estimations of the characteristics of its inner background radiation. More details about the project can be found at http://home.fnal.gov/ sonnensn/ArSummary.pdf.

To-do list:

- Construct the (cylindrical) ion chamber: determination of the components and putting together the pieces.
- Connect the chamber (filled with air) to a high-voltage generator and take first data samples.
- Fill the chamber with Argon extracted from the air (predominantly ^{40}Ar with traces of ^{39}Ar), and as soon as available with depleted Argon from underground gas wells
- Take into account the results from the simulation program Garfield when setting up the initial conditions of the ion chamber.
- Take a new set of data samples.
- Final step: replace the gaseous Argon with liquid Argon and repeat the procedures.

1 Introduction

First of all, a few comments on the state of the experiment. As of the time of finishing this first draft, the experiment is still not properly working. We were able to do a couple of measurements while the chamber was filled with atmospheric Argon. We observed pulses whose amplitude was in the range expected for cosmic rays, but also much greater amplitudes. The latter most probably have their origin in impurities in the chamber (dust particles, for example). On my last trip to Fermilab, we therefore decided to disassemble the detector and clean it one more time. I will see what changes will occur on the measurements. Ideally, the out-of-range pulses will be gone and all we observe is cosmic ray radiation and radioactive decay of ^{39}Ar, even though the setup was not yet sensitive enough to detect the latter during the first set of measurements. I will then work on the distinction between these different kind of sources and connect a multi-channel analyzer to collect the data and carry out the statistics of the pulses. In a broader context, the hope is to have available an ion chamber that is able to measure the radioactive decay of the gas inside it. The aim is to fill it with depleted Argon from underground wells and extract information on the isotopic mixture of that gas. If the ratio $^{39}Ar/^{40}Ar$ is low enough, this gas constitutes an excellent medium for a dark matter detector. At this moment, we next step is to get the setup working properly. We can test the performance of the setup by placing it near a radioactive source of which we know the decay rate and look if we can get this rate from measurements on the detector.

Update 2nd draft A few weeks ago, first measurements were taken while the detector was placed near a radioactive source. Detailed setup and results can be found below in section 3.

2 Experimental setup

The setup consists of a series of measurement devices, interconnected between each other. In this chapter, each of them will be described and put in context with respect to the whole setup. Let us start with the detector itself, the ion chamber.

2.1 The ionization chamber

The radiation detector is a cylindrically shaped ionization chamber, detecting the effects produced by a charged particle passing through the chamber. An electric field is applied inside the chamber, so that free charged particles move towards one of the two electrodes, therein creating a electric current which can be measured. For the chamber used in this experiment, the center electrode consists of an copper rod placed along the horizontal axis of the cylinder. The rod is connected to the outside of the chamber through a high-voltage feedthrough. The feedthrough deserves a paragraph in its own, and is described below. The outer shell of the cylinder constitutes is at ground potential. When a voltage is applied, this particular geometry creates an electric field that is inversely proportional to the radius. Free charges created in the chamber (by a cosmic ray hitting it and transferring its energy to the gas inside the chamber, for example) move towards one of the electrodes under the influence of the electric field and create an electric current. Assuming that all the charges are being collected at the electrodes, the current constitutes the *ionization current* which can be measured. Let us now turn to that part of the setup which allows us to extract information about the origin of the radiation.

2.2 Pulses and Pulse-Shaping

It is important to understand the relationship between a signal in the detector and the pulse appearing on the screen of the oscilloscope. This paragraph explains why and how a 'brute' signal in the detector is *shaped* into a pulse permitting the experimenter to read off a maximum of information on the oscilloscope. The ion chamber in this experiment is operated in pulse mode, as opposed to current mode where the average rate of ion formation in the chamber is measured. In pulse mode, each quantum of radiation gives rise to a pulse. Let us have a short look at the circuit representing an ion chamber operating in pulse mode. A power supply provides an initial voltage V_0 between the electrodes. In the absence of any radiation causing the formation of ion pairs, the so-called signal voltage is zero (see figure). However, as soon as one or more ion pairs are formed within the chamber, they move toward the electrodes and cause the initial voltage V_0 to drop. The measured signal voltage across the resistance is not zero anymore, but exactly the amount by which V_0 has dropped. If the circuit time constant is much larger than the time it takes for the ion pairs to drift toward the electrodes, it can be shown [1] that the signal voltage $V_R(t)$ takes the form

$$V_R(t) = \frac{n_0 e}{dC}(v^+ + v^-)t \tag{1}$$

as long as $t \leq \frac{x}{v^-}$. n_0 is the number of formed ion pairs, e the electronic charge, d the distance between the electrodes and $v^+(v^-)$ the drift velocity of the positively (negatively) charged ions. C is the capacitance. It is also assumed that all the ion pairs are formed at a distance x away from the cathode. When $t > \frac{x}{v^-}$, the electrons have drifted toward the anode and the second term becomes a constant[1]. Consequently, for $\frac{x}{v^-} < t < \frac{d-x}{v^+}$, V_R takes the form

$$V_R(t) = \frac{n_0 e}{dC}(v^+ t + x) \tag{2}$$

Finally, when t becomes larger than $\frac{d-x}{v^+}$, $V_R(t)$ becomes a constant equal to

$$V_R(t) = V_R = \frac{n_0 e}{C} \tag{3}$$

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[1] This always happens faster than the time required for the positively charged ions to move toward the cathode, because the latter's drift velocity is much smaller

A plot of this function whose derivative has two discontinuities (at $t = x/v^-$ an $t = (d - x)/v^+$, respectively) can be seen below. The measured value is the constant $V_R = \frac{n_0 e}{C}$ from which one can immediately deduce the number n_0 of ion pairs originally formed in the chamber.

2.3 Preamplifier

The incoming radiation produces in the ion chamber a bunch of free charges that move toward one of the two electrodes. The total charge Q however is too small to produce a significant signal pulse. It is therefore natural to 'amplify' the signal before it enters the measurement device. This signal amplification usually takes place right after leaving the detector. The electronic device making this possible is called a *preamplifier*. The preamplifier does not modify the pulse, i.e. the pulse shape occurs at a later stage. What it does is to take the input signal or input voltage V_{in} with has a specific amplitude and modifies the latter in a way that the amplitude of the output pulse (corresponding to the output voltage V_{out}) is proportional to the initial amplitude. The amplifier used in this experiment has the highest signal-to-noise ratio of all suitable amplifiers the market has to offer. When setting up the experiment, we could not, however, connect the preamplifier right after the detector: the input voltage of $5000V$ was too high for the device. For that reason, we built a decoupling box between the detector and the preamplifier. The input voltage for the preamplifier then is much smaller and within the limits it can sustain. But another issue needs to be taken into account. The simplest decoupling box one can imagine consists of a resistance in series with a capacitance. A current corresponding to the high voltage enters the box through a cable which has a connection to the detector through a resistance. The cable itself then connects to a capacitance before leaving the box and entering the preamplifier. The aim is then to measure the signal with respect to ground. As mentioned in the above paragraph, however, we are now in the situation of a ground loop with its own current. The remedy to this is to place a resistance between the entering grounded cable and the leaving grounded cable, precisely because these two potentials are not exactly the same, ground potential.

The applied high voltage charges the capacitor which has a capacitance of $180pF$. Negative charges accumulate on one side, while positive charges accumulate on the other. If now a spark is released inside the ion chamber (due to an impurity causing a locally intense electric field, for example), all the negative charges on the detector side flow toward ground. Consequently, there is nothing there to hold back the positive charges on the other side of the capacitor, and these charges all flow into the preamplifier. In other words, a huge current enters the resistance of the preamplifier which breaks down. The understanding of the breakdown was not straightforward and it took us a while to figure out what caused it. This is why it has been decided to disassemble the whole detector and (hopefully) remove the impurities. This has been done successfully, there aren't any discharges of this type anymore, and we are now able to safely make use of the setup to extract information about the signals of interest.

2.4 Multichannel analyzer

How do we extract information about the radiation? This is done via a multichannel analyzer. This device measures the differential pulse height spectrum coming from the detector and converts it into a digital signal which can be analyze on a computer. Generally one can choose the number of channels one wishes to have. If the number of pulses is large enough, the number of channels can be chosen to be very high, each having a very small width. The resolution of the spectrum is then very close to the real, continuous spectrum. If rate of counts is small however, one has to chose a smaller number of channels with a larger width. The multi-channel analyzer (hereafter MCA) is an extremely useful device to extract information about the energy distribution of events in a detector. In this paragraph, we will describe its main features. The MCA records the number of pulses within a small increment of pulse height H, $\Delta N/\Delta H$. The increment in the pulse height ΔH is called the *channel width*. The smaller the channel width ΔH, the closer the result is to the theoretical curve dN/dH. Plots of $\Delta N/\Delta H$ are called *pulse height spectra*.

2.5 Noise

A very important task is to reduce the noise as much as possible. In this experiment, noise can originate from cosmic rays, but 'internal' noise is present as well, as we could deduce from the observed pulses on the oscilloscope. By internal noise we mean pulses that originate from impurities inside the chamber, but also locally intense electric fields due to the geometry of the detector. Another source of noise comes from the coaxial cables interconnecting the different constituents of the setup. [2] These cables possess characteristic internal resistance which can contribute to the noise in the output signal. In our setup, we try to use as short cables as possible, minimizing the internal resistance. Finally, a significant source of noise can originate from *ground*

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[2] Coaxial cables are generally used for these kind of detectors.

loops. Ground loops arise when both the source and the measurement devices are connected to the ground, which is the case in our experiment. The internal resistance and/or any resistance placed in between the source (i.e. the ion chamber) and the measurement instruments cause a voltage between the two grounds and thus a current will flow in the so-called ground loop. This current, then adds up to the current one is interested in and thus modifies the 'real' current due to the events in the ion chamber. The undesired voltage may exceed the voltage due to a signal by several orders of magnitude. One way to avoid the emergence of a ground loop current is to ground all the devices at a single point. In that case, the ground loop voltage is negligible with respect to the signal voltage.

3 First Results

Besides the use of a test pulser, two different radioactive sources were used for a first calibration of the detector. The first one is the Cobalt isotope ^{60}Co with a half-life of 5.27 years. Its decay goes as follows:

$$^{60}Co \xrightarrow{\beta-decay} {}^{60}Ni^{*} \xrightarrow{2\gamma} {}^{60}Ni \tag{4}$$

In 0.12% of the cases, the β-decay is followed by emission of only a single gamma particle to reach the ground state, i.e. the initial β decay particle carries more energy.

The second source used in the experiment is the Americium isotope ^{241}Am with a half life of 432.2 years. Its decay goes like

$$^{241}Am \xrightarrow{\alpha-decay} {}^{237}Np^{*} \xrightarrow{\gamma' s} {}^{237}Np \tag{5}$$

In 0.35% of the cases, the decay only involves the α particle and no gammas are emitted.

Let's start with the setup without any source, detector decoupled, and the pulse generator connected to the charge sensitive preamplifier. In other words, the test pulse undergoes an amplification before being recorded. The oscilloscope reads the preamplifier output, and the multi-channel analyzer (hereafter MCA) records both the voltage of each pulse, proportional to the energy, as well as their rate of occurring. In theory, the preamplifier output is constant, so by recording the amplitude distribution for a given input voltage allows us to characterize the electronic noise of the system and compare it with the value given by the manufacturer. It should be emphasized that these measurements were taken with a different preamplifier than the one used previously. The reason is that the first one broke down, probably because the input voltage was set too high. This preamplifier was actually the lowest noise preamplifier on the market, so it would have been an excellent component in our setup. However, since one also wants high voltage input, it was decided to use a different preamplifier with a slightly higher noise level. The preamplifier currently in use has an equivalent noise charge of 230 electrons root mean square (hereafter RMS) (shaping time 1μs), according to the manufacturer. Here, this is checked for different voltage inputs. [3] For a given pulse amplitude, one gets a peak at some specific channel. According to the preamplifier manufacturer, an input voltage of 1V corresponds to 1pC of charge, or $\frac{10^{-15}}{1.6 \cdot 10^{-19}} = 6250$ electrons. Below 9 is a plot with straight line fit for six data points, i.e. peak values and corresponding channel number for six different input voltages of the pulser. The MCA recordings for each one of these data points (recall we just selected the channel with the peak value of the number of electrons) are also shown below, as well as the recordings for the two sources. For all but the last plot, the graphs show the number of electrons as a function of the channel number. The last plot then show the amplitude of each peak (in terms of number of electrons) and their location (in terms of channel number), i.e. channel number as a function of electron number[4]. Also, for the plots with no source present, the left portion is just noise, possibly background radiation. The straight line fit is consistent with what could be expected; it shows the linearity of the electronics. What needs to be done now is to carefully examine the RMS in terms of number of electrons for each peak and compare it with the value given by the manufacturer. It is extremely important to know precisely this number in order to separate an ^{39}Ar decay from noise.

4 Outlook

The unwanted discharges posing problems have now disappeared, and we are on track now to start the main measurements. We used the sources ^{60}Co and ^{241}Am and analyzed the recordings of the MCA. It is not yet sure that depleted Argon from underground wells will be accessible before May this year, but if so, we could finally measure the isotopic contamination of ^{39}Ar with an extremely sensitive setup. A significantly lower ratio of $^{39}Ar/^{40}Ar$, i.e. a much lower proportion of the radioactive isotope would imply that a liquid Argon detector would be among the most sensitive dark-matter detector in the near future, and certainly more sensitive by at least an

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[3] The previous preamplifier had a noise charge of 335eV FWHM with a 1μs shaping.

[4] for the last plot, each axis has to be rescaled by a factor 1000

order of magnitude than currently running experiments. What can be said already is that the isotopic ratio of depleted Argon is at least 20 times lower than that for atmospheric Argon, but this is still a conservative estimation and the ratio may even be much lower.

References

[1] G. Knoll, "Radiation Detection and Measurement", Second Edition , Wiley (1988).

[2] J. Keithley, "Low Level Measurements", Second Edition (1998), Keithley Instruments.

[3] Elena Aprile, Aleksey E. Bolotnikov, Alexander I. Bolozdynya, Tadayoshi Doke, "Noble Gas Detectors". Wiley (2006).

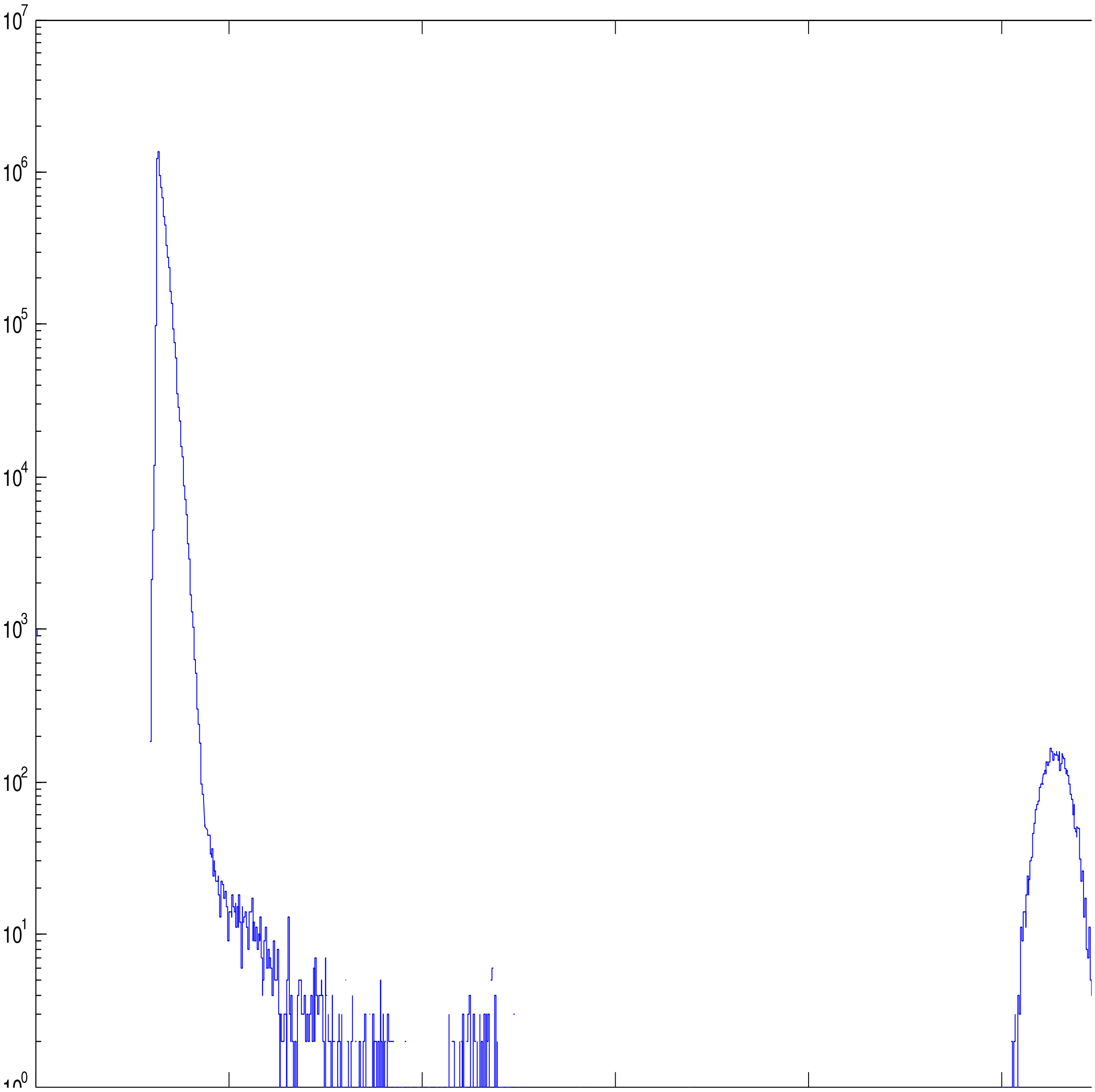

Figure 1: *3mV input*

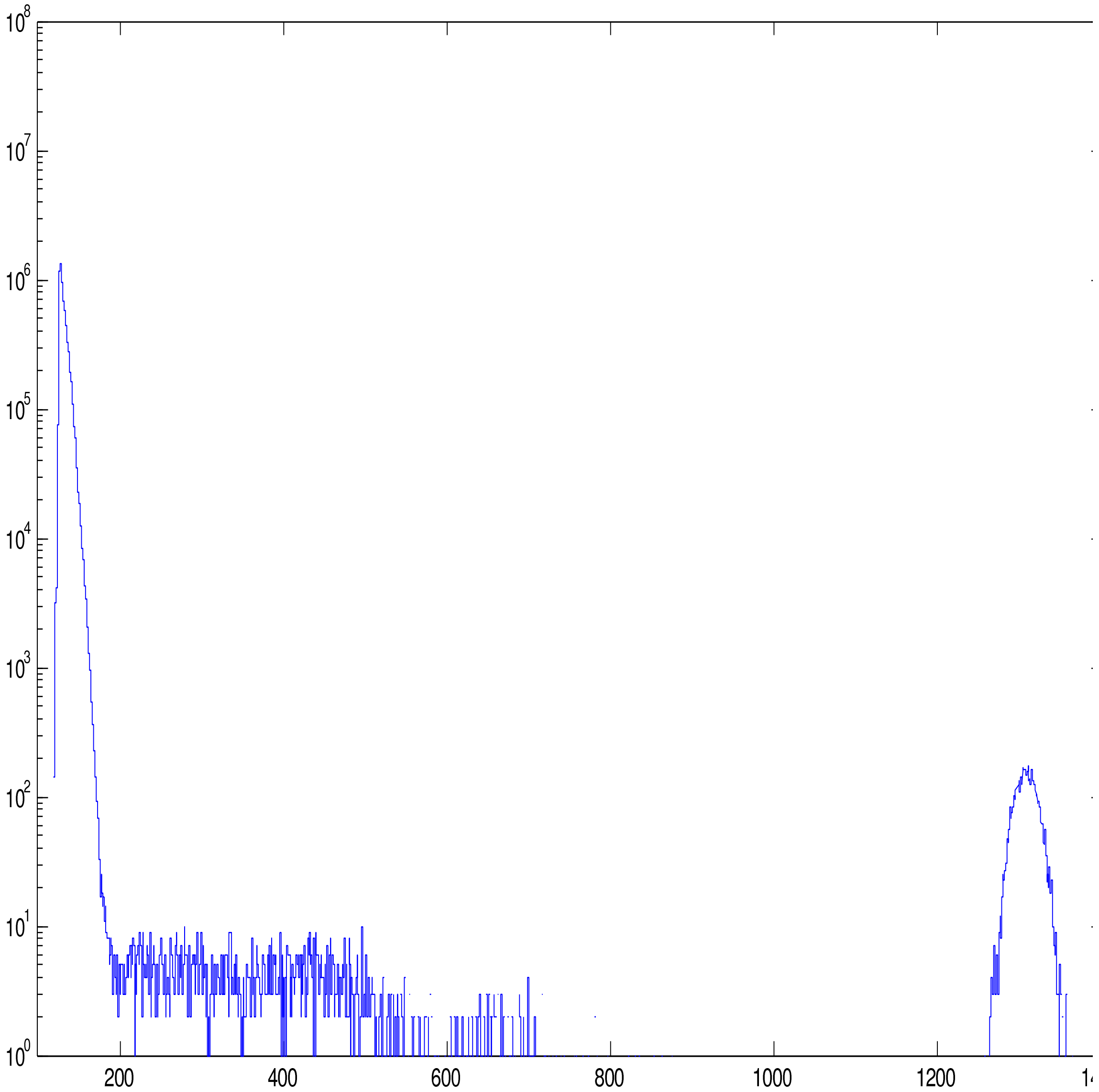

Figure 2: *5mV input*

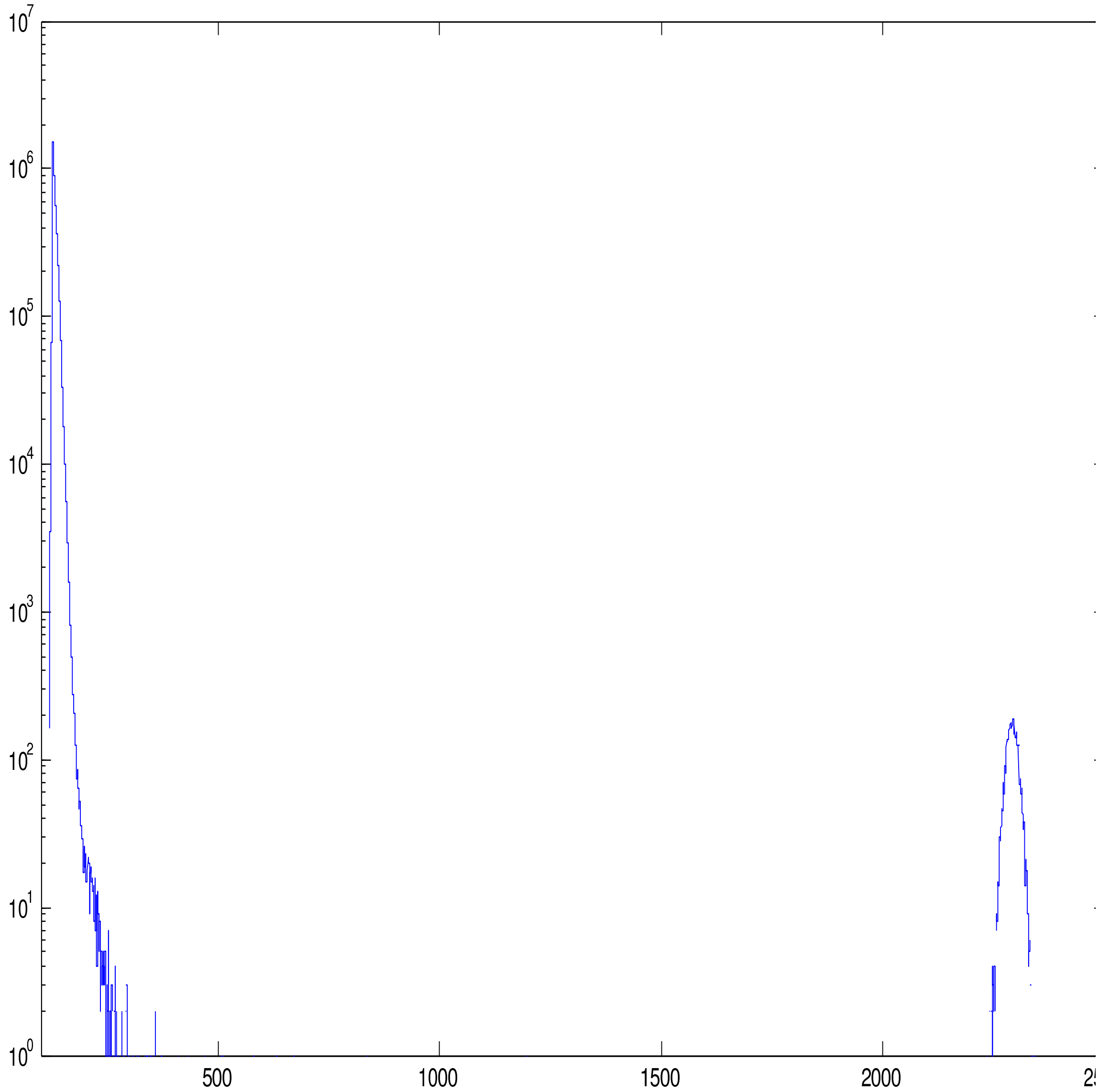

Figure 3: *8mV input*

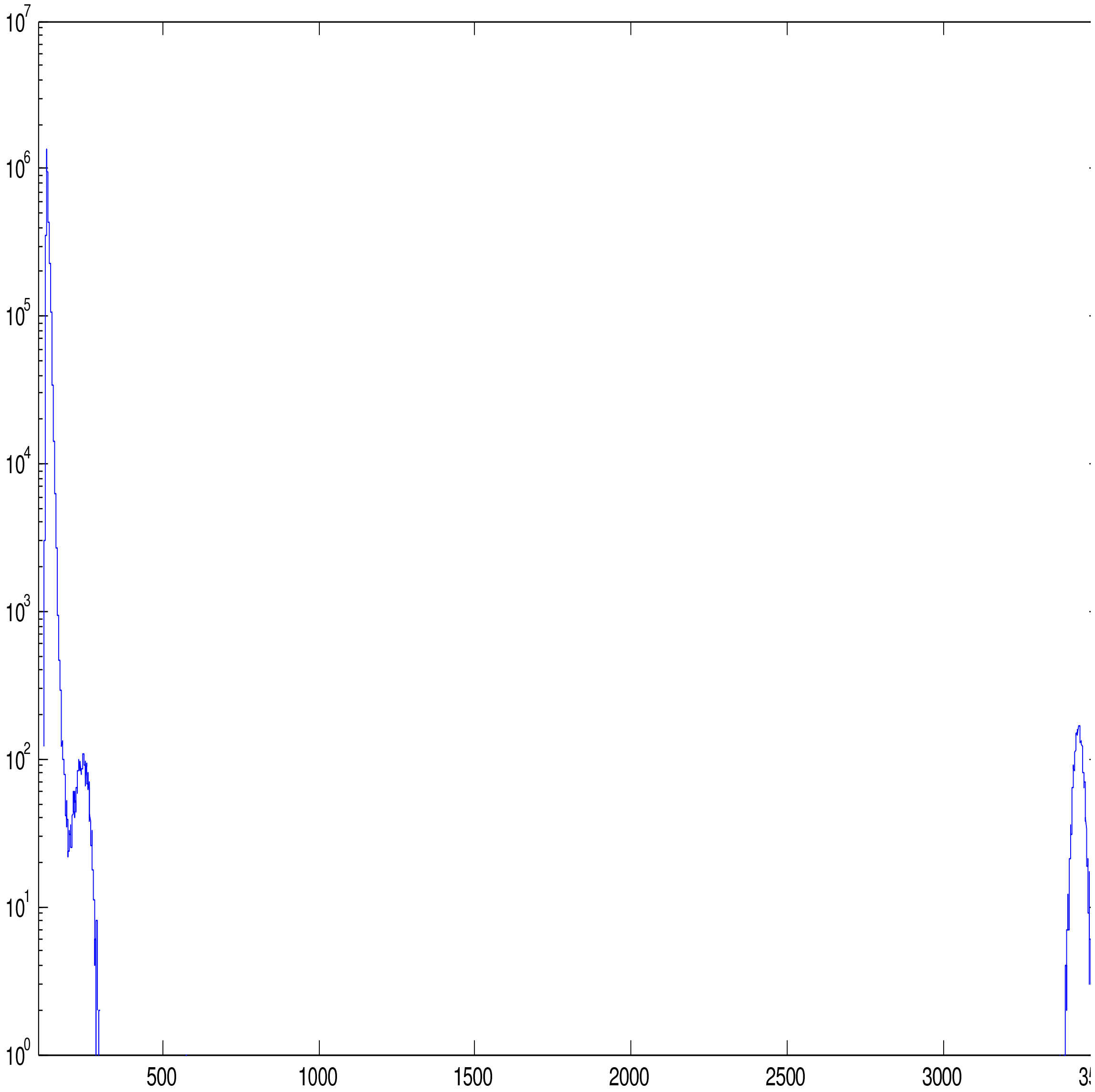

Figure 4: *11mV input*

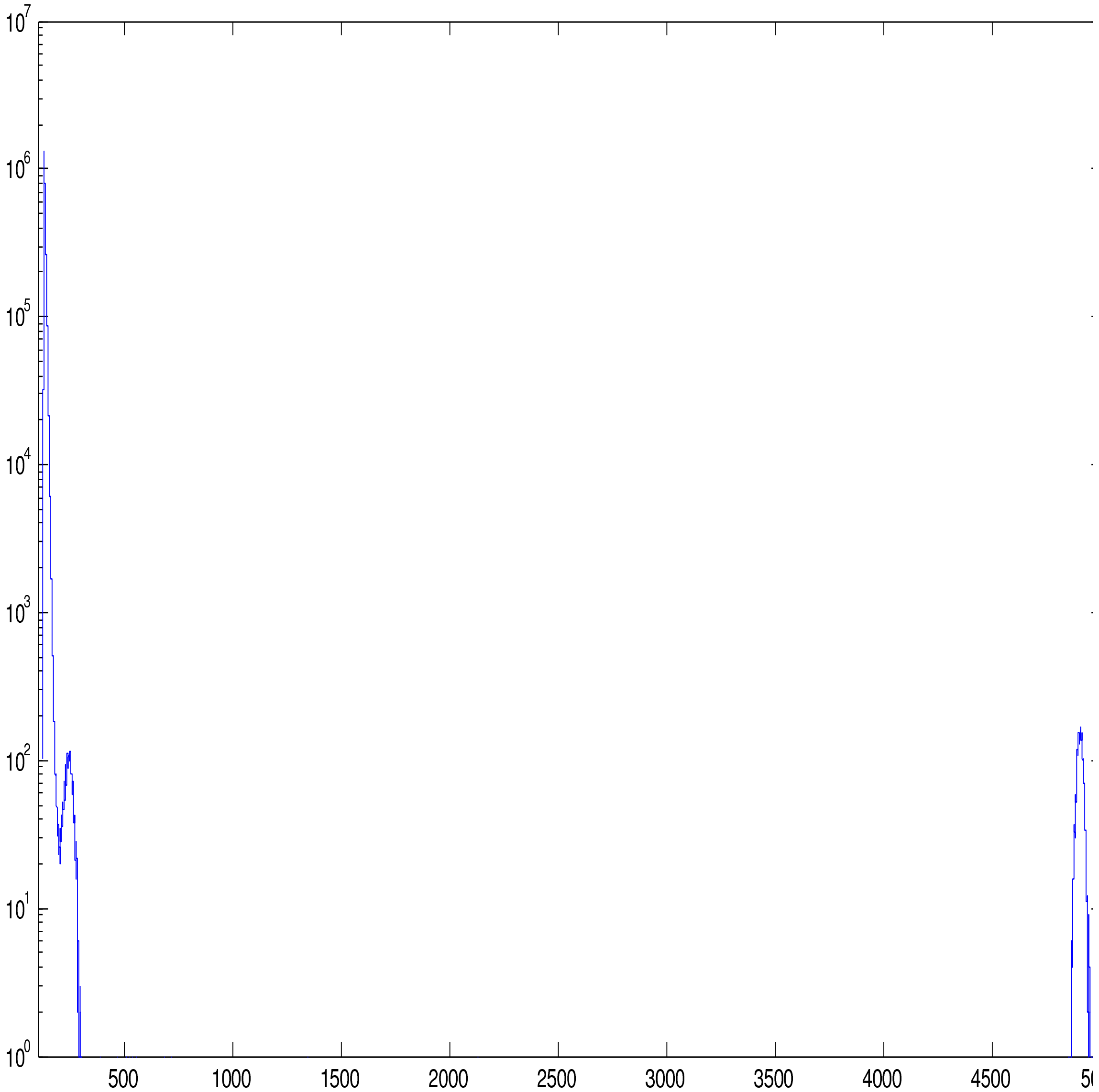

Figure 5: *16mV input*

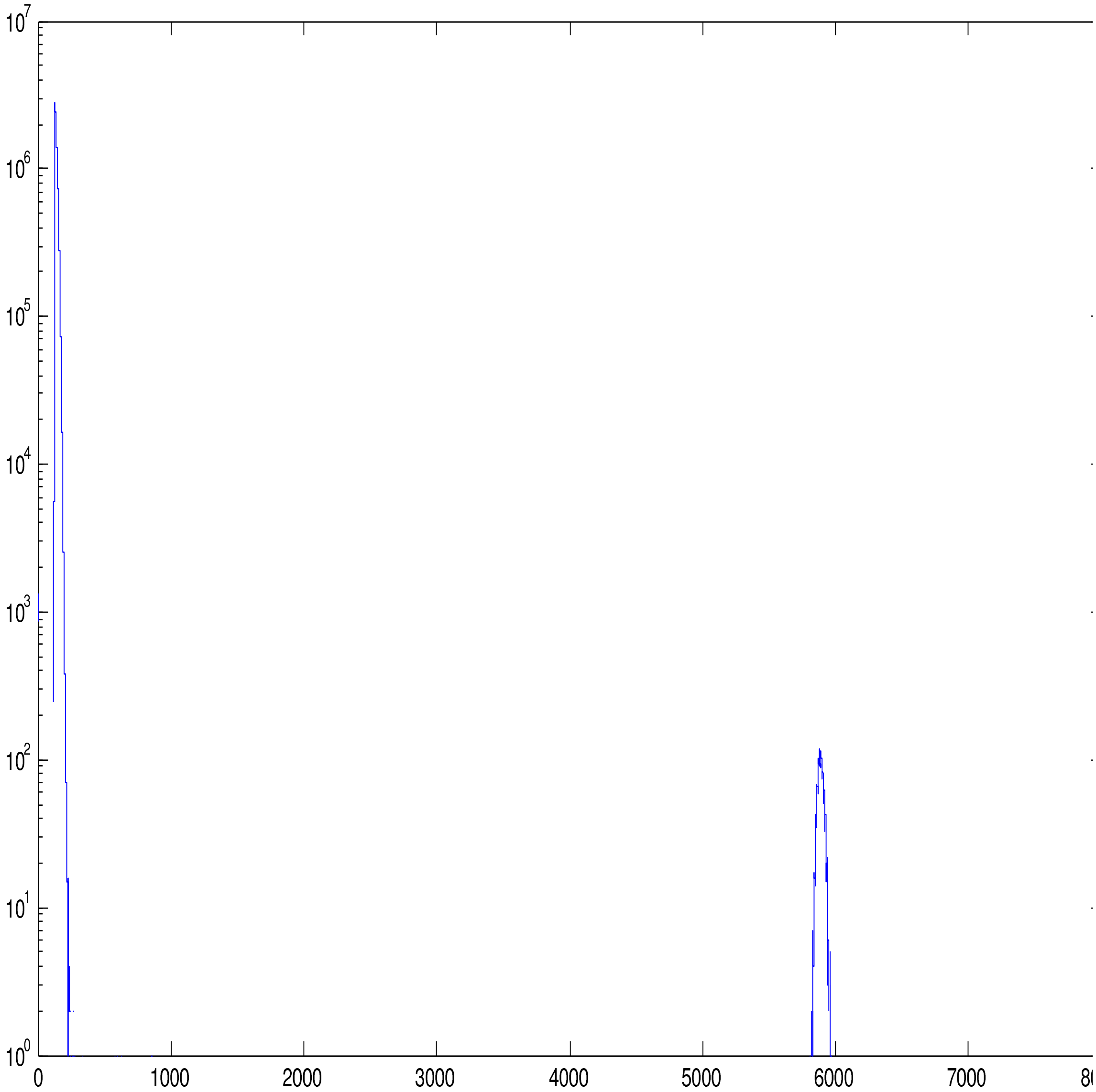

Figure 6: *18mV input*

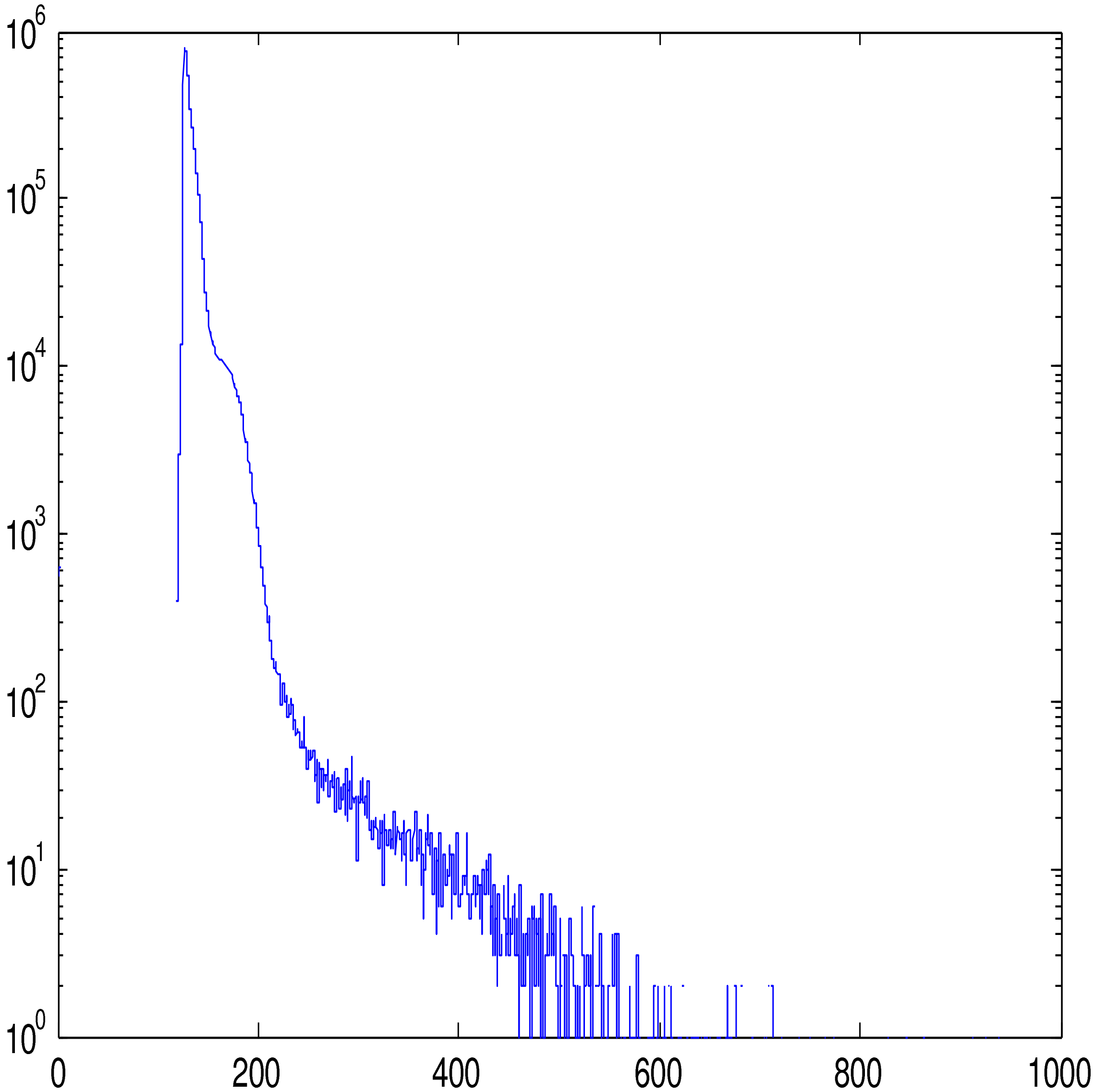

Figure 7: ^{241}Am *source*

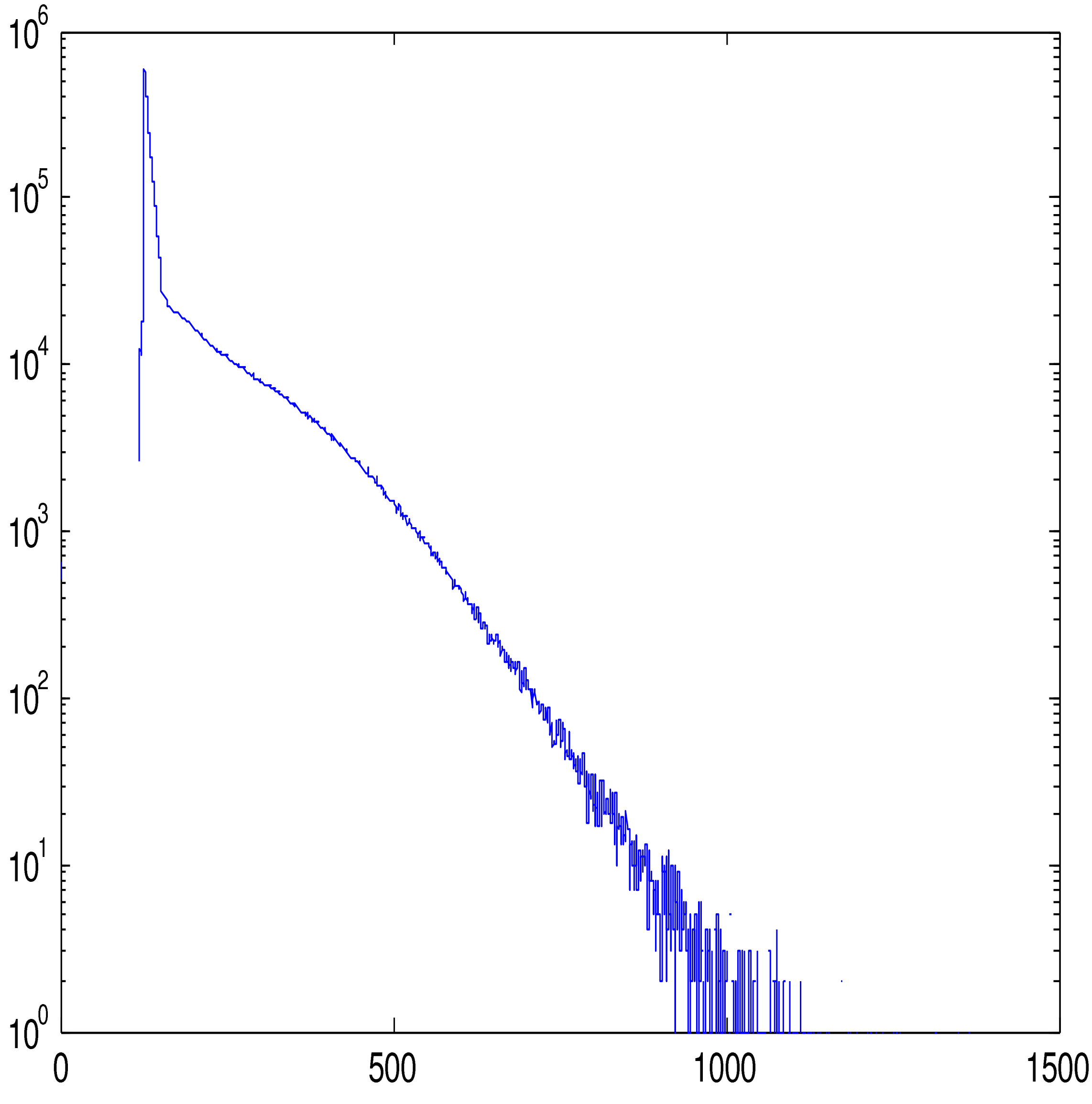

Figure 8: ^{60}Co *source*

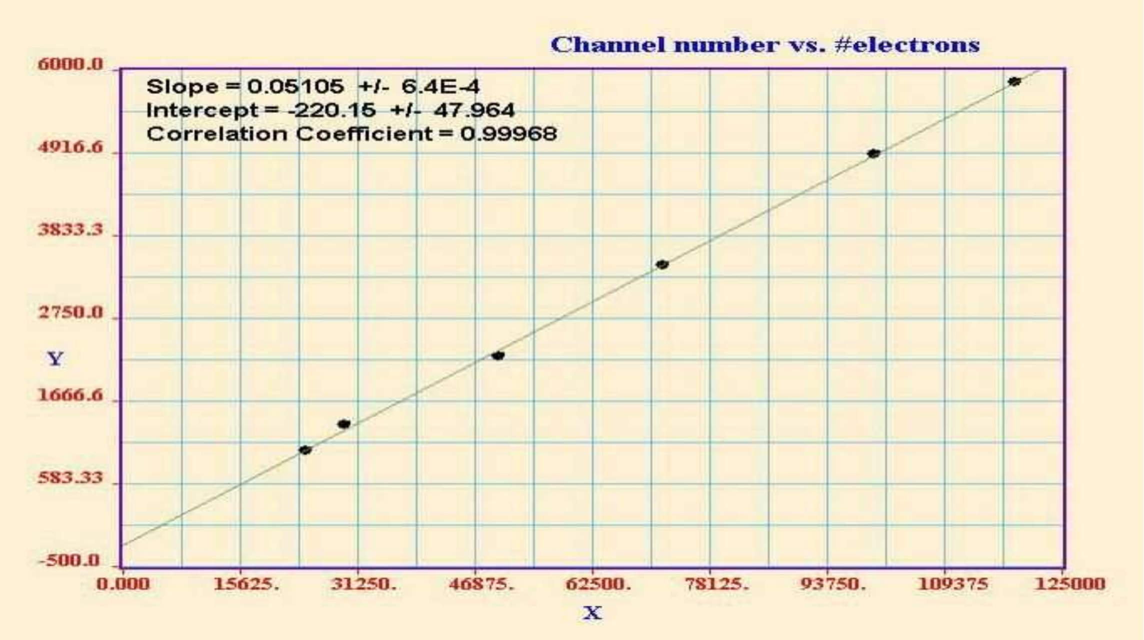

Figure 9: *The MCA recordings for six data points*