Measurement Model of an Alpha Spectrometer for Advanced Undergraduate Laboratories

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Abstract

In this paper, we present the modeling aspects relevant to students at the advanced UG level for using an Alpha Spectrometer as a measurement tool for nuclear physics experiments. The four stage modeling methodology for construction of theoretical models is utilised as a framework to understand the various aspects of an alpha spectrometer. The presentation specifically focuses on alpha spectrometer 'AlphaSpec-1K' indigenously designed and developed by us. The spectrometer output is interfaced to the USB port of a PC, and the associated software 'CNSpec', which is licensed under open-source terms, has built-in features to fit, calibrate, and perform various analysis of the obtained spectrum. The spectrometer is designed to detect alpha energies in a full scale range of 10 MeV with a resolution of 81 keV at 5485 keV. It is calibrated using ^{241}Am and tested for linearity using ^{229}Th multi-peak source, and as a final step, has been validated using ^{212}Bi, by verifying its spectrum with published literature, as well as calculating its half life to better than 1% accuracy.

1 Introduction

One of the major goals in imparting physics education is to incorporate good laboratory practices alongside theoretical modeling and computer simulation based approaches. Physics Education Researchers have deliberated on various aspects of laboratory practice such as learning goals for advanced physics labs [1], cognitive task analysis [2], lab environment with regards to engagement of teachers and students in lab activities [3], and the mode of assessment [4]. Especially, the PER group at Colorado, Boulder has developed a set of learning goals for physics laboratories [5], wherein

emphasis is laid on measurement models. They contend that modeling the measurement process is important since the instrument should not merely remain a black box for the students and that they should understand the principles of operation, key model parameters, and limitations pertaining to the ideal functioning of the apparatus. Our PER group, in collaboration with the teaching lab of the outreach cell of IUAC New Delhi, is focussing on developing lab experiments for nuclear physics along with activities, simulations, and demonstrations to go hand-in-hand with the theoretical course. As a part of this effort, we are in the process of developing experiments based on Geiger counters, as well as gamma and alpha spectrometers, where in we have two primary goals:

1. Design and development of low cost alpha and gamma spectrometers

2. Design and development of nuclear physics experiments using non-enriched sources

A key area of focus is the effective implementation of these outcomes in labs through the application of PER practices. We have submitted a paper [6] to the same journal, wherein we have discussed an experiment to study the alpha spectrum and half-life of ^{212}Bi. The Bi source was prepared using electrolysis of non-enriched $ThNO_3$ powder and the spectrum is obtained using our indigenously developed alphaspectrometer 'AlphaSpec-1K'[7].

Modeling the measurement apparatus and familiarisation with its usage are crucial precursors to actually utilising them to perform experiments. Here, we utilise the modeling theory structure suggested by Hestenes [8] which has been employed almost as a methodology. Its inherent design helps systematise our understanding of the scientific process of learning, as it is very effective in applying the constructivist pedagogy wherein students are guided (typically using the Socratic method) to build their understanding of the current topic based on their previous knowledge. Even though the modeling theory suggested by Hestenes is for constructing theoretical models, we have used the same technique to model the measurement apparatus, here the alpha-spectrometer 'AlphaSpec-1K' by using the tools of an experimentalist instead of those of a theoretical physicist. In the next section, we give a brief outline of the four stages in the modeling structure with reference to the alpha spectrometer, and in subsequent sections, discuss the various stages in detail with focus on experimental aspects such as characterisation,calibration, and data collection.

2   Modeling the alpha spectrometer

In order to build the alpha spectrometer, one needs a sensor (a transducer along with the required electronics) that detects the energy of the alpha particles and outputs a

proportional voltage signal. In this section, we model the detection process in tune with the modeling theory proposed by Hestenes [8] which has the following four stages.

1.Description Stage: Here, we describe
(i) the object which is the detector,
(ii) the process involved, that is, creation of charge pairs within the depletion region, and finally,
(iii) the interaction responsible for creation of charge pairs when alpha particles deposit their energy in the depletion region.

2.Formulation Stage: While the theoretician formulates the laws and principles involved with regard to the process and interaction, the experimentalist focusses on the detection procedure, which involves the following three steps:

(i) capturing the alpha particles without any loss of their energy prior to entering the detector's active volume

(ii) converting the alpha energy into a measurable voltage through various signal processing electronic circuits

(iii) acquiring the data by a computer for visualization of the spectrum, and for subsequent statistical analysis
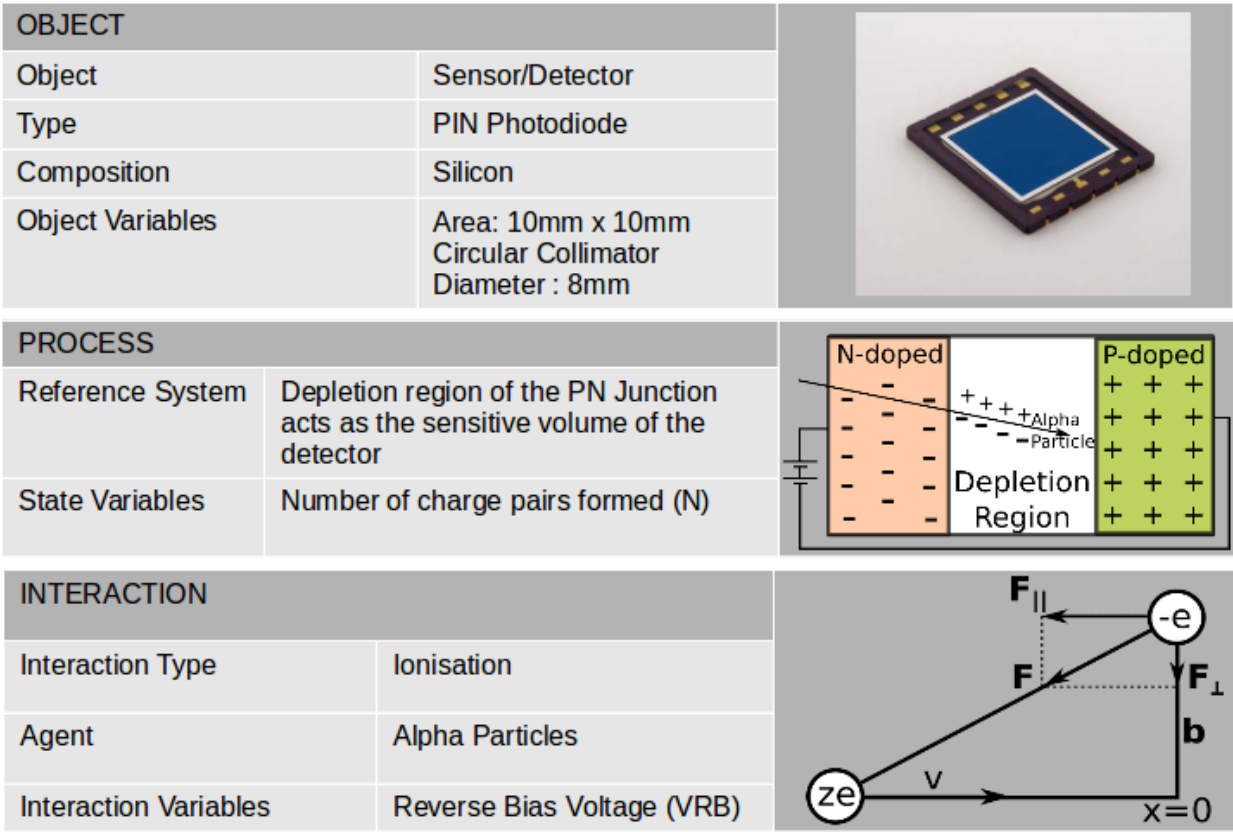
Even though our approach involves construction of the apparatus from an experimental design perspective [2], from the modeling perspective it suffices to deal with understanding the principles and reasoning behind the need for various aspects of the apparatus design. Even though this understanding would help in troubleshooting a malfunctioning apparatus, it might not enable carrying out repairs. From a researcher's point of view, careful insight into the measurement process enables proper identification of any anomalies in the final spectrum output. This is an important learning goal.

3.Ramification Stage: From a theoretical perspective, this stage involves solving the equations related to the model object and obtaining the emergent properties in a form that can be compared with experimental outcomes. From an experimental angle, this stage can be termed the testing part, which is also an important learning goal for advanced laboratories [5]. For the measurement model, this stage involves studying the manufacturer's data with regard to usage of the apparatus. In the case of the alpha spectrometer, this involves obtaining the spectrum and calibrating it to obtain the emergent properties such as energy and intensities of the peaks.
Typically, the manufacturer performs experimental runs in which the apparatus along with the detection system is tested with a well known α source such as ^{241}Am, and then specifies the calibration procedure for converting the channel number into useful energy information. Further, the apparatus is tested for understanding the effect of source-detector distance, and also that of

Figure 1: The object, process and interaction are described in detail with relevant diagrams alongside

OBJECT		
Object	Sensor/Detector	
Type	PIN Photodiode	
Composition	Silicon	
Object Variables	Area: 10mm x 10mm Circular Collimator Diameter : 8mm	

PROCESS		
Reference System	Depletion region of the PN Junction acts as the sensitive volume of the detector	
State Variables	Number of charge pairs formed (N)	

INTERACTION		
Interaction Type	Ionisation	
Agent	Alpha Particles	
Interaction Variables	Reverse Bias Voltage (VRB)	

air pressure on the obtained spectrum to finalise the ideal vacuum for experimentation. Finally, the detection system is tested for linearity by using a source of ^{229}Th which has distinct multiple peaks with known values that can be easily resolved. In the current paper, these are discussed as part of the ramification process, as these could be performed by the students in the lab as well, given the availability of enriched sources of ^{241}Am and ^{229}Th. We also intend to make this a part of the familiarisation procedure by implementing this

testing and calibration phase using ^{212}Bi, a non-enriched source prepared using the electrolysis process discussed in [6].

4.Validation Stage: The obtained outcomes (emergent properties) are validated with known predictions by using either theoretical considerations, or previously known experimental results. The apparatus is now ready for experimentation with other sources for validation, and to undertake research with unknown sources.
In the following four sections each of these

stages is discussed in detail with appropriate flow diagrams and results.

3 Description stage

a) Principle of operation: Typically an alpha detector consists of a semiconductor PN junction connected in reverse bias mode so as to create a depletion region that acts as an ionisation medium to convert the alpha particle energy into electron-hole pairs which move towards the electrodes due to the applied electric field. The small amount of charge generated as a result of one alpha particle depositing its entire energy in the depletion region is proportional to its energy, and this charge is a measurable quantity.

b) Description of the detector: The **type** of detector that we have employed is a PIN photodiode whose **composition** is Silicon. The detector (**dimensions** specified by the manufacturer [7]) has $10mm \times 10mm$ surface area and $5mm$ thickness. In front of the detector is a circular collimator of 8mm diameter whose purpose is to prevent alpha particle incidence near the boundary of the detector where its behaviour is non-linear and results in erroneous readings.

c) Description of the Process: The PIN photodiode is connected in reverse bias so that a depletion region of the junction is created. The reverse bias voltage (V_{RB}) is chosen such that the width of the deple-

tion region is maximum, and hence the active volume of the detector is maximised. This also reduces the junction capacitance and thereby reduces noise. The current produced due to a voltage V_{RB} across depletion region width l is given by [9].

$$I = nq\mu_n \frac{V_{RB}}{l} \tag{1}$$

Where n is the number of charges (q) generated in the depletion region, and μ_n is the mobility of the charge carriers. μ_n is typically constant for low V_{RB}. The electric field across the junction is given by $E = \frac{V_{RB}}{l}$. The number of charges (n), is the **state variable** associated with the process.

d) Description of Interaction: The **type** of interaction responsible for creation of electron-hole pairs is ionisation within the depletion region. The **agent** of interaction is the coulomb force between the charged particles and electrons in the neutral material available in the depletion region. An alpha particle (positively charged) with sufficient kinetic energy (implying large velocity) exerts a coulomb force on the electrons in the atom (Figure 1) to escape from the atom, or atleast take it to one of the excited states (leaving the atom in its excited state). The amount of ionisation due to the incident alpha particle of energy E_α is going to be dependent on the active volume available for the particle to completely deposit its energy (a depletion region of width $10\mu m$ should suffice), and in the process, create an equivalent number of electron-hole pairs.The
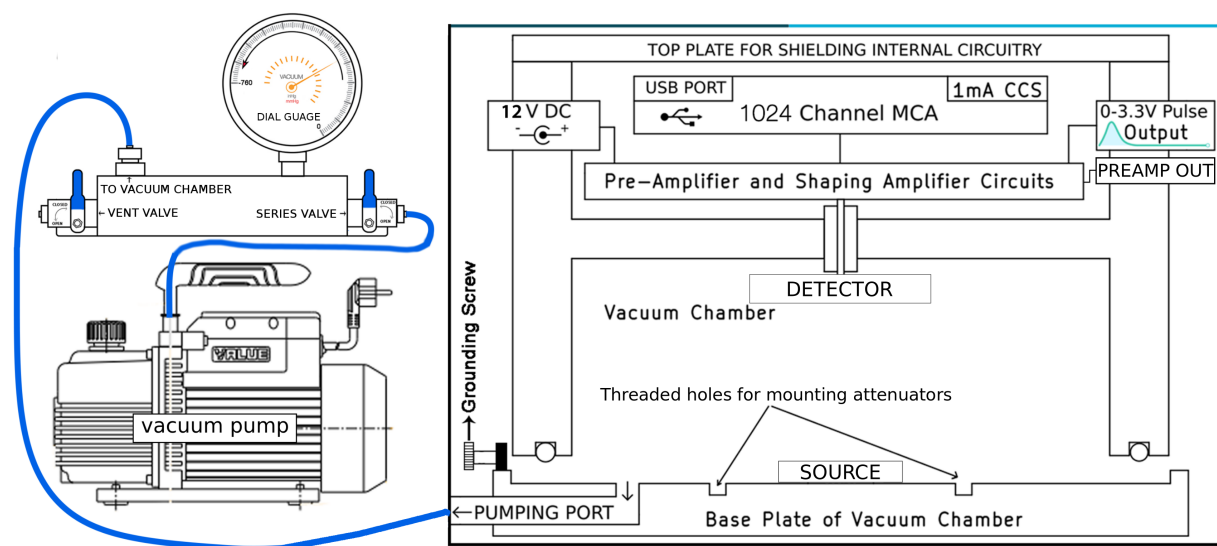
Figure 2: Source-Detector Enclosure Design along with the Vacuum pump and its assembly

energy required to create on electron-hole pair in silicon is 3.62eV, so the total number of pairs generated can be estimated based on the initial energy of the alpha particle. So, the **interaction variable** that affects the process is V_{RB}, which is responsible for the depletion region of thickness l.

4   Formulation stage

a) Enclosure design and Vacuum assembly: The first step is to ensure that only the alpha particles emitted by the source reach the detector without any loss of energy, and that they deposit their entire energy in the detector's active volume to generate a corresponding signal. The sensitivity of the detector to light photons necessisates placement of the source and detector inside an opaque enclosure. The enclosure is de-signed to be air tight so that vacuum can be created within it to avoid loss of energy of alpha particles due to scattering with air. The design of the chamber along with the vacuum pump and accesories are shown in Figure 2.

The second step involves various stages of processing the signal to obtain the final spectrum reflective of the number of charge carriers deposited at various energies, and is outlined in the form of a block diagram in Figure 3 which is discussed below:

b) Conversion of charge to voltage: The signal from the detector is available as the number of charge carriers that have reached the electrodes, which is then converted into a corresponding output voltage by utilising a charge sensitive preamplifier. The main role of the preamp is to ensure impedance matching between high impedance at the detector side (i.e. input), with the low
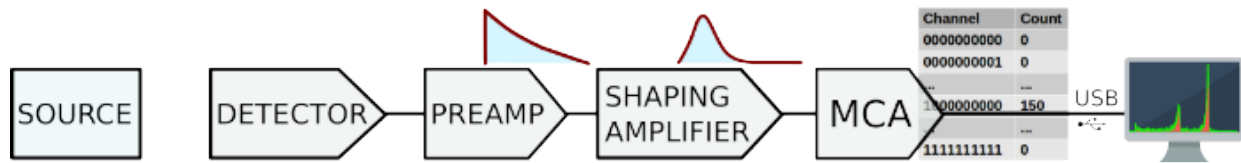
Figure 3: Signal Processing Electronics: The step by step process of conversion of alpha energy into a measurable quantity such as voltage that maintains a predictable proportionality is indicated as a flow diagram

output impedance of the post-processing electronics. This also improves the signal-to-noise ratio (SNR).

In this spectrometer, the designed preamplifier (open source hardware available at [10]) has a MOSFET at the input in cascade with a bipolar junction transistor (BJT) . A feedback capacitor present in the preamp is used to decide the gain/charge-sensitivity. A high value resistor (typically $100M\Omega$) is connected in parallel to discharge the capacitor (1pF) . In principle, an alpha particle of 1MeV energy should give a total charge ($Q = \frac{1*10^6*1.6e^{-19}}{3.62}$) [9] and the output voltage of the preamplifier is given by $V = \frac{Q}{C} = \frac{1*10^6*(1.6*10^{-19})}{3.62*(1*10^{-12})} = 44.2mV$.

To study the output characteristics of the preamplifier, we have chosen ^{241}Am as the alpha source since it has a single alpha emission at $5.485MeV$ energy. As per our calculations, we should obtain about 242 mV as the peak voltage of the corresponding output from the preamplification stage, but due to the non-zero capacitance of the detector, the measured voltage was in the range of 150-200mV.

The preamplifier output provided in Figure 4 as H is for visualization purposes only as it has been attenuated by buffering circuits, and is not indicative of the actual output value. The rise time is determined to be close to 50nS, and it takes nearly 1mS to drop to 50% of its peak value, thereby giving it a distinct sawtooth appearance.

Because of these very short rise and fall times, the output voltage signal of the preamp cannot be easily digitized, and we need to process the signal further, which is done using a shaping amplifier.

The output of the shaping amplifier is also available via a BNC socket for external monitoring with an oscilloscope or a separate MCA. The maximum height of output pulses has a range of 0-3.3V, where 0 indicates the absence of a pulse, and 3.3V indicates an incident alpha particle with energy close to the maximum permissible value of 10MeV. The shaping amplifier [11] has a differentiator circuit followed by a second order active integrator to obtain a near gaussian pulse as shown in 4 as I. The peak value of this pulse is to be sampled and digitized.

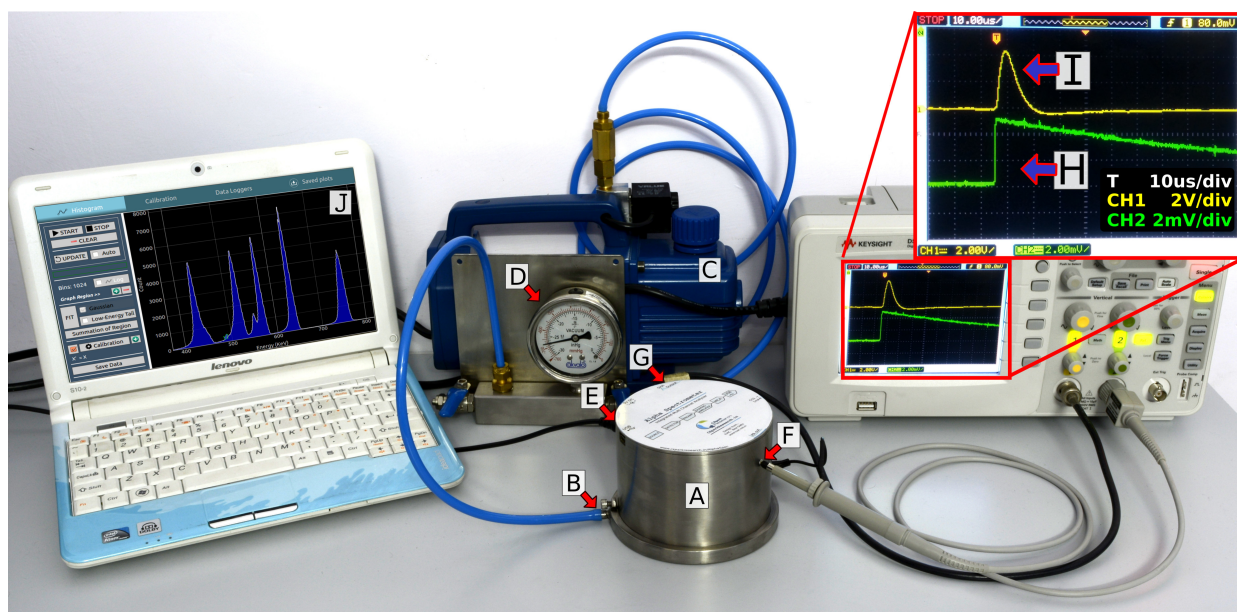c)   Digitization of the voltage signal:

Figure 4: Entire experiment setup of the Alpha Spectrometer '**AlphaSpec-1K**' showing the source-detector enclosure(A) connected via the vacuum inlet port(B) to the pump(C), with pressure monitoring by a dial guage(D). It is connected to a laptop(J) via the USB port(E). Signal outputs from the pre-amplifier(F) and shaping amplifier(G) are connected to a 50MHz oscilloscope where the nature of these signals are shown as traces (H) and (I) respectively. The time scale of the oscilloscope is $1\mu S$/div, and the voltage scales for preamp and shaping amplifier are 2mV/div and 2V/div respectively. Signals have been offset for clarity.

The pulse is accepted if the amplitude is greater than the threshold value (to avoid very low energy peaks which might not be due to alpha particles) which is set to 50mV. The combination of peak detector and Analog to Digital Converter (ADC) is designed to convert the peak height (i.e. proportional to detected alpha energy) into a digital number, and the histogram data of energy vs number of counts is generated with the help of a Multi Channel Analyzer (MCA). The MCA is designed to have 1024 channel(1K) resolution, with an input voltage range of $0-3.3V$. This limits the

energy resolution to $\frac{10MeV}{1023} = 9.7keV$.

d) Spectrum: The alpha spectrometer hardware performs a variety of tasks ranging from detection of the pulse, post-processing of the signal, and also sorting the signals on the basis of their peak height into predefined bins by the MCA. This information consisting of a table of number of pulses registered in each channel is stored in the in-built microprocessor of the MCA in a linear array, and must now be transferred into a computer via the USB communications port in order to visualize, analyse, and interpret the data.
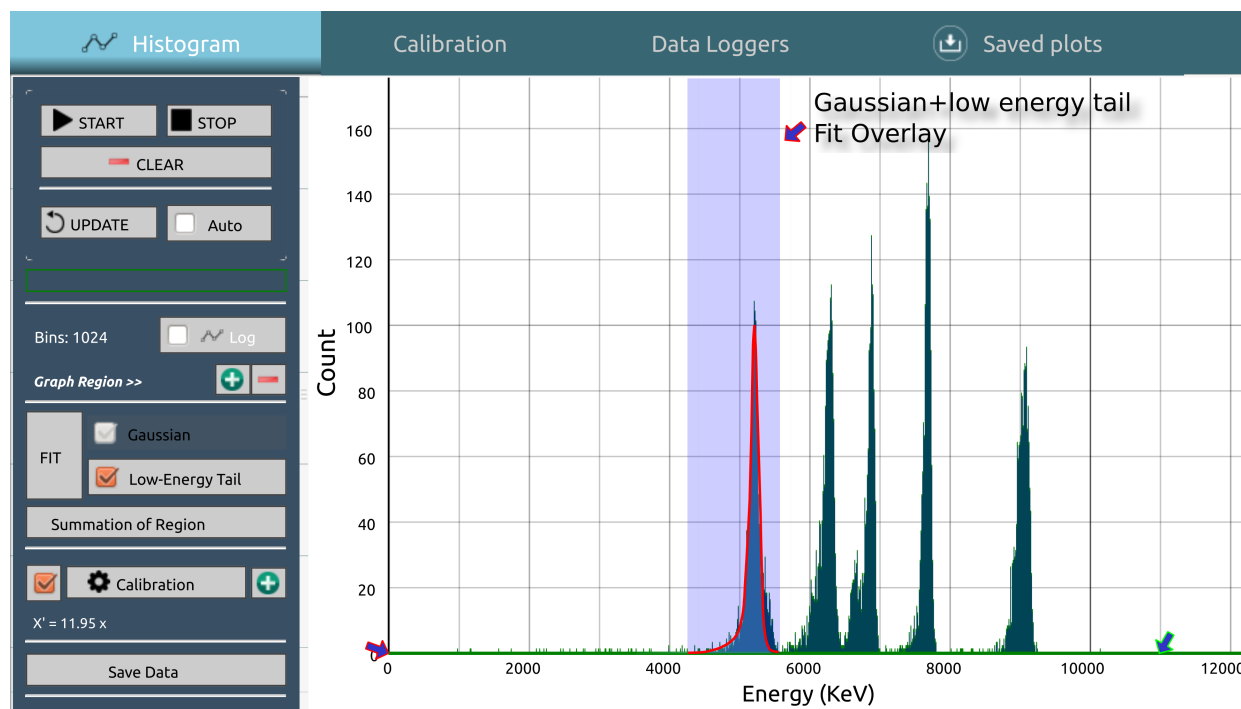
Figure 5: A Screenshot of the open-source software provided with the Alpha Spectrometer '**AlphaSpec-1K**':

e) <u>Housing the electronics</u>: Considering the highly sensitive nature of the signals from the detector, it is important to place the preamplifier very close to the detector to avoid noise and leakage. Equally important, is the need to house the signal processing electronics in an electrically shielded enclosure. To ensure this, a cylindrical structure segmented along the central plane via a 3mm stainless steel sheet was designed2, and one segment was made vacuum tight with provisions for a sealing gasket and an inlet port for a pump as shown in Figure 2. The detector is electrically connected to the signal processing electronics via a very short (5mm) feedthrough which is

also vacuum tight. With this design, we have effectively placed all electronics in a Faraday cage.

f) <u>Software:</u> The final step is to implement a software that shall plot the acquired data in real-time and have utilities for data analysis. The open-source software **CN-Spec** written in the Python programming language employs a variety of powerful utilities such as Numpy, Scipy, and PyQtGraph for various mathematical and visualization purposes. It acquires the data from the hardware, and plots it in the form of a histogram showing channel number (corresponding to peak voltage proportional to alpha energy) on x-axis, and the number of charged parti-

cles received at each channel on the y-axis, as shown in Figure 5. The key analytical features incorporated as of now in the software are calibration using polynomials up to 2 orders, fitting with Gaussian plus low-energy tail (Lorentzian part) to obtain peak information, and a summation utility to obtain the total number of counts corresponding to a peak.

5   Ramification

Once the spectrum is available, the detection system is in principle ready for experimentation. But first, the proportionality constant between alpha energy and corresponding peak voltage obtained needs to be determined. This process is called calibration.

5.1   Calibration using ^{241}Am

When we place the ^{241}Am source, the α-energy spectrum corresponding to it must now appear as number of counts building up around a particular channel number. To determine the appropriate vacuum to be established for effectively neglecting the energy loss due to scattering, we perform the following two steps.

i) To study the effect of source-detector distance at atmospheric pressure:
The ^{241}Am source was placed at a distance of $25mm$ from the detector, and the average channel number (corresponding to energy) of its lone peak was measured. For this, we have implemented a least square fit routine which uses a standard gaussian

function, and record the centroid value (average channel number) for each dataset. The source-detector spacing referred to distance, was reduced in steps of 3mm and the centroid was noted for each distance. In the distance versus channel number plot shown in Figure6(a), the linear dependence of energy loss with source-detector distance at atmospheric pressure demonstrates that the scattering of alpha particles is proportional to the distance travelled in air.

ii) To study the effect of air pressure:
The ^{241}Am source was placed at $30mm$ from the detector. The vent valve was closed, and the pressure inside the chamber was slowly decreased from 1000mbar to 100mbar in steps of 100mbar. The average energy of the peak that accumulates at a particular channel number is obtained at various pressures and plotted in Figure6(b). At 200mbar itself, the peak energy is obtained at channel 469 which corresponds to placing the source at a distance of 3mm from the detector as shown in the previous section. That is, at 200mbar, the scattering losses are almost negligible. Further reducing the pressure to 50mbar is equivalent to placing the source almost in contact with the detector.

The final spectrum obtained by placing ^{241}Am at a distance of 2 cms and a pressure of 50 mBar is shown in Figure6(c). The centroid of the spectrum is found to be located at channel number 496 via a gaussian fitting routine, and since the energy of this peak is well known to be at 5485 keV, one can fit a
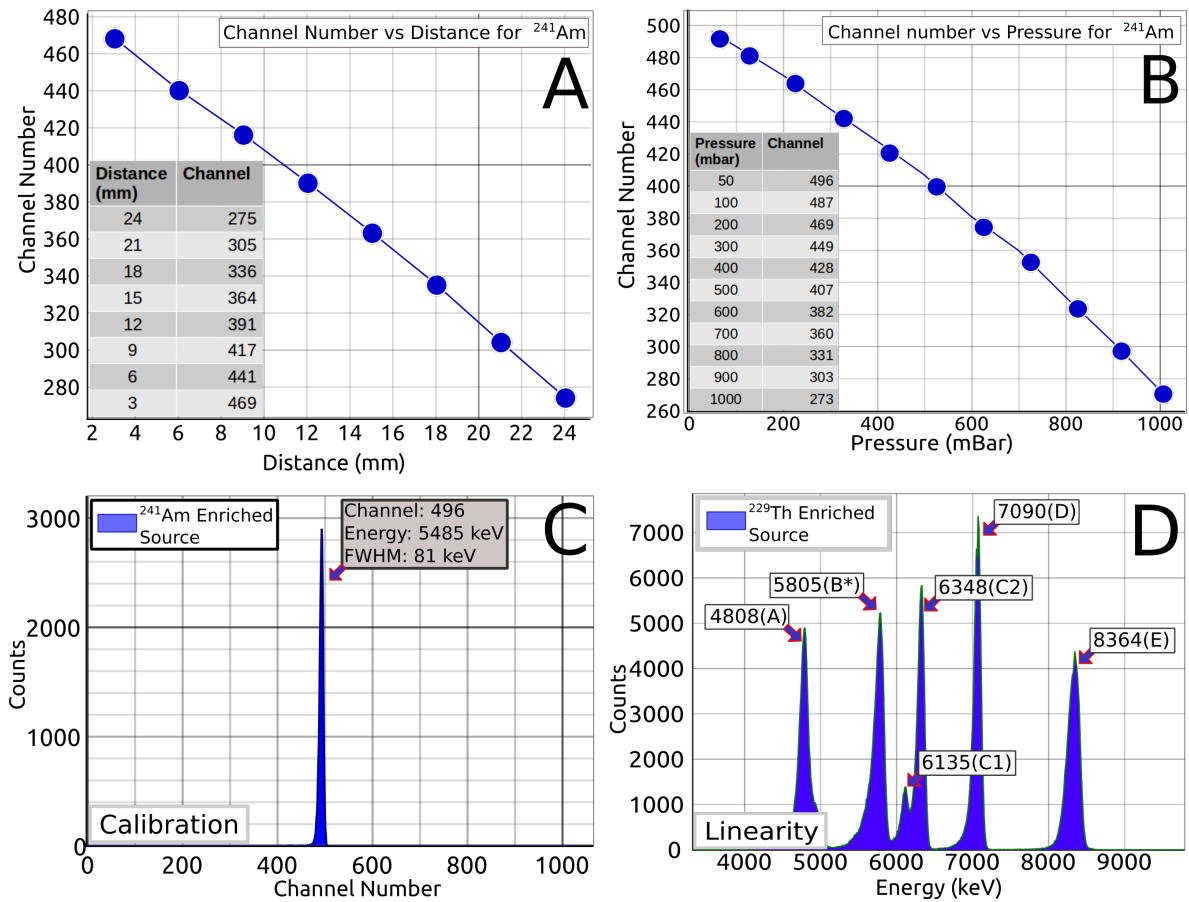
Figure 6: a) Effect of source-detector distance on the centroid of the lone peak of ^{241}Am. b) Effect of air pressure is studied for the same centroid . c) Alpha spectrum for ^{241}Am under 50mBar vacuum with source-detector distance = 2cm . d) Alpha spectrum for ^{229}Th under similar conditions as in (c)

calibration polynomial as follows:

$$Energy = \frac{5485}{496} \times channel\ number \quad (2)$$

An FWHM of 81 keV was obtained via a gaussian fit of the calibrated peak. ^{241}Am enriched source is commonly employed for single point calibration purposes since it produces a single peak at a known energy. However, since single point calibrations are not equipped to correct offset errors, it is advisable to use a source with at least two decay processes with alpha particle emissions at known energies, such as ^{212}Bi. We can now cross-check if our calibration remains linear over the entire range of 10 MeV. A good source for checking this is the multi-peak source ^{229}Th whose energies are compiled from ENSDF and shown in Table 1.

5.2 Linearity check using ^{229}Thorium

To verify the linear energy response of the detector, a ^{229}Th source is placed at 20 mm from the detector and the data is acquired

Table 1: The radioactive decay chain of ^{229}Th with alpha energies (with intensities more than 5%) and their respective intensities are compiled from ENSDF. The beta decays are also shown for the sake of completeness.

Parent	Daughter	$E\alpha$	$I\alpha$	$t_{\frac{1}{2}}$
^{229}Th	^{225}Ra	4845.3(A)	56.2	7340y
		4814.6	9.3	
^{225}Ra	^{225}Ac	β	-	14d
^{225}Ac	^{221}Fr	5830 (B*)	50.7	10d
		5732	8	
		5790.6	8.6	
		5792.5	18.1	
^{221}Fr	^{217}At	6126.3(C1)	15.1	4.9m2
		6341(C2)	83.4	
^{217}At	^{213}Bi	7066.9(D)	99.9	32.3ms
^{213}Bi	^{209}Tl	5869	93	45.59m
^{213}Bi	^{213}Po	β	-	45.59m
^{213}Po	^{209}Pb	8375.9(E)	100	4.2us
^{209}Tl	^{209}Pb	β	-	2.2m7
^{209}Pb	^{209}Bi	β	-	3.25h14

under a vacuum of 50 mbar. The obtained spectrum, shown in Figure6(d) has been calibrated, and the peaks correspond to their expected energies with an accuracy better than 1%. The peak $B*$ in Figure 6 corresponds to four values shown in Table 1. Since these peaks have energies too close to be individually resolved by the current spectrometer, we assigned their weighted average of 5817 keV to be the expected value for $B*$. The accuracies of the obtained energies confirms that the linearity of the detector is assured over the full scale range of the instrument to better than 1% .
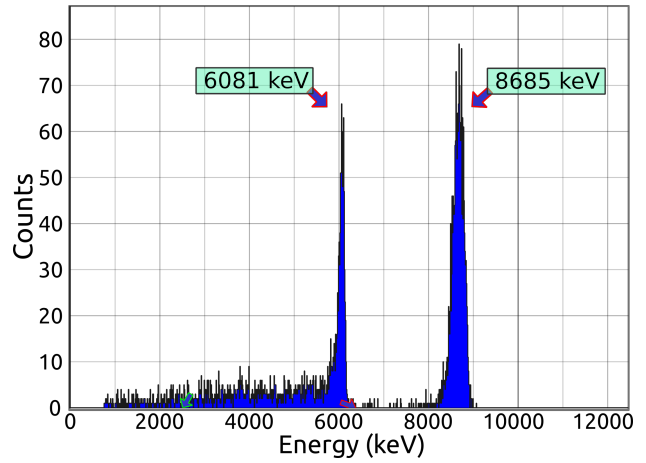
6 Validation
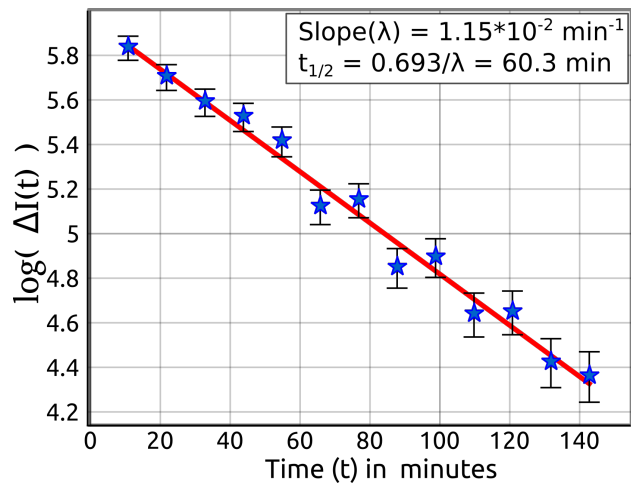

Figure 7: ^{212}Bi Spectrum

Figure 8: Log of activity of ^{212}Bi recorded as a function of time for calculating its half life

In order to validate our instrument, we must now record the spectrum from a third source, and verify that it matches with known values. For this purpose, we have prepared an un-enriched source of ^{212}Bi extracted from Thorium Nitrate salt via elec-

trolysis. The extraction procedure is carefully documented by Swapna et al [6], and their results also include spectrum characterization as well as half-life calculations.

In order to extract Bismuth, 3.5gms of Thorium Nitrate($ThNO_3$) salt was dissolved in 5gms of water. Electrolysis of this solution using 20mA current and lead foil electrodes for 10 minutes yielded a greyish film on both electrodes. The anode was placed in the vacuum chamber at a distance of 1cm from the detector to acquire the spectrum.

It had two distinct peaks with centroids at 6081 keV and 8685 keV as shown in Figure 7. These values correspond closely with the known energies from the decay chain of ^{212}Bi which are 6062keV and 8785keV [6] with percentage errors of 0.31% and 1.13% respectively.

Since the peak formed around 6081keV may also contain contributions from various trace isotopes from the Thorium-232 series as explained by Swapna et al[6], we used the higher energy peak formed around 8685keV for half-life calculations.

The activity was obtained by determining total counts under the 8685 keV peak in 12 minute intervals. The log of the activity has been plotted as a function of time in Figure 8. The slope of the regression line determines the decay constant λ(shown in inset of Figure 8) using which the half-life is determined to be 60.3 minutes with an uncertainty of 2.4 minutes. It agrees with the expected value of 60.5 minutes to an accuracy of 0.33%.

7   Conclusions

We have presented the way to model an alpha spectrometer, **AlphaSpec-1K** developed by us, so as to familiarize students with:

- the basic principles involved in the detection process (theoretical aspects)

- the need for various parts of the spectrometer (design aspects)

- the outcomes at various stages (troubleshooting aspects)

- the way to calibrate it and test for its linearity (analysis aspects) and finally

- perform experiments using it (application aspects)

To help develop a structured approach, we have utilised the framework proposed by Hestenes for actualising theoretical models and have applied it to modeling a measurement apparatus such as an alpha spectrometer.

8   Acknowledgment

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