REMOTELY ACCESSIBLE RADIATION DETECTION LABORATORY FOR DISTANCE EDUCATION

A Thesis

by

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ABSTRACT

An essential part of any student's curriculum in nuclear engineering is performing radiation detection experiments to gain a better understanding of the physical processes that are occurring. However, not all institutions are capable of providing the equipment or radiation sources necessary for such labs, nor do long-distance students have the ability to readily access these facilities. This research seeks to help remedy this problem by developing and testing a remotely accessible radiation detection laboratory system. Through this work, a student can connect to the experiment station via remote desktop and then conduct a variety of radiation detection experiments.

This research is a proof of concept for the implementation of a remote lab that is accessible through an internet connection. The system consists of a host computer, attached radiation detection hardware, motorized equipment to allow manipulation of the lab elements, and a camera to provide visual feedback to the students. As part of distance laboratory courses, students would remotely access the host computer and conduct the experiments from their location. In this work, three different experiments were set up on the system and tested. The experiments were the identification of an unknown source using a sodium iodide (NaI) detector, determination of uranium enrichment using a high purity germanium (HPGe) detector, and dead time determination with a Geiger-Müller tube.

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CONTRIBUTORS AND FUNDING SOURCES

Contributors

This work was supervised by a thesis committee consisting of Dr. Marianno and Dr. John Ford of the Department of Nuclear Engineering and Dr. Dylan Shell of the Department of Computer Science and Engineering.

The experiment tests and feedback in Section 5 were provided by Costner Quick of the Department of Nuclear Engineering.

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NOMENCLATURE

API	Application Programming Interface
eV	Electron-Volt
FWHM	Full Width at Half Maximum
GM	Geiger–Müller
HPGe	High-Purity Germanium
IT	Information Technology
LEU	Low-Enriched Uranium
MCA	Multi-channel Analyzer
MID	MCA Input Definition
NaI	Sodium Iodide
NEMA	National Electrical Manufacturers Association
NID	Nuclide Identification
ROI	Region of Interest
VI	Virtual Instrument

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1. INTRODUCTION

1.1 Motivation

With the modern marriage of online communications and traditional education institutions, the opportunities for education are greater now than they have ever been. The internet and online information databases have allowed the propagation of information and research to accelerate at a breakneck pace. However, even with these advances, the institution of education itself remains remarkably difficult to free from its physical limitations. After all, to receive a higher education it is usually necessary to uproot and move to an educational institution for several years, which poses a significant hurdle for many. Not all prospective students have the means or funds to relocate themselves across the country or, potentially, the world for years at a time. Additionally, not all education institutions may possess the resources necessary to provide for a high-quality learning experience in certain courses, while the institutions that do are unable to share them.

The solution to these issues has been distance education. Distance education is, in short, any delivery mode for education in which students and teachers are separated in space or time. Far from a 21st century invention, distance education really got its start when reliable postal services were established (Mood, 1995). However, education by mail could never truly compare to a traditional format, hampered by the delay inherent to mail services and the difficulties this brings to correspondence. With the advent of the internet, however, distance education became a serious consideration for universities. It became possible to offer courses at a distance that stand on par with those offered in person. Currently universities have been successful in providing quality distance degree programs to students who would otherwise be unable to participate (Getchell, 2014), though by no means are all degrees offered. Distance education still has a great deal of room for development.

Texas A&M University offers a variety of Master's degree programs for distance education, including a number of Master of Engineering degrees. However, during the time this work was executed, nuclear engineering is not among them (Texas A&M University, 2017). Given the relative rarity of nuclear engineering programs (of all engineering disciplines, only petroleum engineering has fewer accredited programs (U.S. News, 2017)) due to the prohibitive costs and legal difficulties involved, it is unfortunate that one of the departments that could stand to gain the most from being available for distance education is largely unavailable. A handful of online nuclear engineering programs exist, but they are mostly bereft of lab classes, often featuring simulations at best. Penn State's online nuclear engineering course, for example, has a single laboratory course that is only necessary if a student does not meet certain prerequisites, and must be performed on-site anyway (Pennsylvania State University, 2017). Laboratory experience is an important component of any nuclear engineering program, and to remove it in its entirety would be unfortunate. In order to address this issue, the creation of resources to allow for distance lab courses is necessary.

1.2 Research Objectives

The main goal of this research was to prototype and test a laboratory system that enables remote access to a variety of radiation detection experiments, with flexibility for further expansion and adaption in the future. This was done through the assembly of the system's host computer and software, adding and assembling controlled motor components and radiation detectors to the system to allow for the completion of several radiation detection experiments, and then completing these experiments remotely through the use of the system.

The foundation of the system is a host computer that holds the necessary software, controls the lab equipment, and is in turn controlled by the distance student. From here, the system is expandable, with the ability to add additional controlled components, detectors, and other features as is necessary to allow for experiments. An important feature of this system is that it must be easy to use and difficult to misuse; students should have as little exposure as is reasonable to the code and extraneous features of the system and its software.

Three test experiments were designed and tested on the system, each covering a different aspect of radiation detection. This ensures the adaptability of the designed system and demonstrates its applicability to a range of radiation detection experiments. The three experiments that were tested are: 1. Source identification and quantification using scintillation detectors; 2. Uranium enrichment calculation with HPGe detectors; and 3. Dead time determination with GM detectors. Each of these experiments was set up by the author and conducted by a distance student through their internet connection.

At the conclusion of the experiments, feedback was used to improve the system and set clear objectives for future developments on it.

2. PREVIOUS WORK

Attempts at solving the problem of bringing lab coursework into online degree programs have been made many times and with a variety of proposed solutions. Among these solutions are virtual labs and remote labs. Both of these are made with the goal of allowing students to receive a lab experience or something very close to it without requiring that the student physically be present at the university. Both can be completed over the internet.

Virtual labs are effectively an experimental simulation. The student is given a program that allows them to manipulate elements of a virtual lab. The system will adjust and produce results based on the user's set parameters (Son, Narguizian, Beltz, & Desharnais, 2016). While the experiment in question is not being physically performed in real time, this is meant to give the student a close approximation to what will happen when it is performed. Obviously this has some weaknesses; since the experiments are programmed and not being performed live, results are deterministic. There is little opportunity for students to run into the same challenges that can occur when attempting such experiments by hand. Another difficulty in the implementation of virtual labs is that, since they are entirely computerized, each experimental detail needs to be custom-made. There is little room for re-use from experiment to experiment, meaning more work needs to be put into the creation of each simulated experiment. Despite the challenges, implementations of virtual labs can be seen throughout the academic world. For example, a virtual physics lab course was put into practice at the International IT

University in Kazakhstan, featuring a full suite of virtual experiments for physics students (Yevgeniya, Viktor, & Madina, 2017).

Another approach to online laboratories is in presenting the experiments to students through video. Such a system was presented and student-tested for a physics course at the University of Camerino in Italy (Amendola & Miceli, 2016). In this approach, students are given a video recording of the experiment being conducted by an instructor. Students then take the data from the recorded lab, analyze the data, and present a report based on their findings. While this is an approach that is simple and quick to set up, it does mean that the students have no real opportunity to conduct the experiment themselves; they are only observing, not actually working with the lab elements.

Remotely controlled labs for the purpose of distance education are not unheard of, even in the field of nuclear engineering. In 2011 a similar remotely accessible radiation detection lab was implemented at Clemson University for the purpose of potential on-line radiation detection courses (Kopp, 2011). Similar to this work, the lab at Clemson utilized a host computer and software-controlled motor components to manipulate lab elements. Major differences include that the Clemson lab utilized custom-written LabVIEW programs in order to analyze radiation detection data from the MCAs. This has the effect of making implementation expansions difficult, and has been made largely unnecessary with the improvements in modern commercial radiation detection software. Additionally, the online implementation of the experiments was not remotely tested; experiments were performed from the host computer itself. When this thesis was written, it did not appear that an online degree program involving radiation detection has been implemented at Clemson University (Clemson University, 2017).

3. SYSTEM COMPOSITION

3.1 Host Computer

The core component of the remote laboratory is the host computer. This is the computer students will connect to via Windows' Remote Desktop Connection and use to control the experiment apparatus. The computer used for this project was a Dell Precision T3500 running Windows 7. The full specifications of the computer are shown in Table 1 (Dell Inc., 2010).

Processor	Intel® Xenon® W3503, 2.40 GHz
Operating System	Windows 7 Enterprise
Memory	4.00 GB, 1333 MHz
Chipset	Intel X58
Internet Ports	Two Broadcom NetXtreme Gigabit Ethernet Ports

Table 1 – Host Computer Technical Specifications

In addition to the laboratory software detailed in the following sections, this computer has Remote Desktop capabilities enabled and was connected to two separate networks: a local area network comprised of the host computer and the experimental system components such as motors and detectors, and the Nuclear Engineering Department's network. Remote students connect to this computer through this second network. The component network is only accessible through the host computer.

Students connecting to the computer need to have an online account with both Texas A&M University and the nuclear engineering department. In addition the student must be registered to the computer's list of permitted remote desktop users by IT in advance, or they will be unable to connect. This prevents unauthorized users from accessing or tampering with the lab system.

3.2 Canberra Genie 2000

A critical piece of software in the host computer is the Genie 2000 spectroscopy software, developed by Canberra for use with their radiation detection devices. This suite of programs allows students to interface with the detectors used in the experiments, change the settings, and record radiation detection data. The most frequently used program in this software suite is the Gamma Acquisition and Analysis program, which can be coupled to any Canberra MCA.

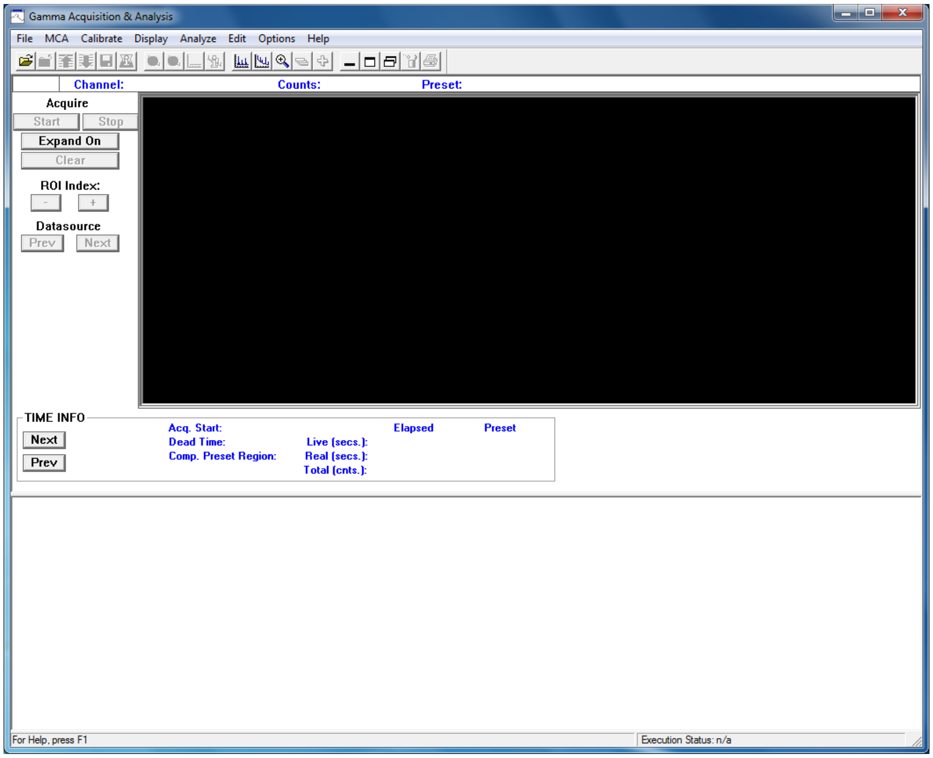


Figure 1 – User interface for Genie 2000 Gamma Acquisition and Analysis.

A picture of the Gamma Acquisition and Analysis program is shown in Figure 1. The recorded radiation spectrum is displayed in real time in the black box, while the results from the various spectrum analyses are output into the large white space at the bottom. Information about the current spectrum is displayed below the spectrum box. This display area gives a variety of information and includes:

- **Time Info**: Presents the time acquisition began, the dead time, the live time, the real time, and the total counts collected. Real time is the total time taken during acquisition (live time plus dead time), while live time is the time for which the detector has actually been able to collect and record radiological data. In other words, the live time is the real time with the dead time taken out.

- **Marker Info**: Genie allows the user to select regions of the spectrum by placing markers that surround spectral features (i.e. peaks). These are called region(s) of interest (ROI). The Marker Info field displays both the channel number and energy (if calibrated) for each marker and the centroid. The integral and area of the ROI is given, along with an uncertainty value for the area. Here, the area represents the net counts in the ROI above background, while the integral is simply the total counts in the ROI. Since the integral is just a sum of the counts, there is no uncertainty associated with it. The field also provides the FWHM and the full width at tenth maximum.
- **Nuclide Info**: Displays helpful information for identifying nuclides. By placing the cursor on a point in the spectrum, Nuclide Info will display a nuclide identity, if any, that has a photon at that energy, along with its half-life and that photon’s yield. Placing it in a highlighted ROI will also give the FWHM and area of the region much like the Marker Info field. It can also estimate the activity of the nuclide, but will only if an efficiency calibration is supplied.
- **Sample Info**: Displays what user-defined sample is being examined, giving details such as the sample title, ID number, type, quantity, and sample geometry. Genie 2000 does not attempt to fill out any of these entries by itself; it is up to the user to enter the pertinent information that is displayed here. This information can be entered in the Sample Info option of the Edit menu. The purpose of this field is to help keep track of previously recorded spectra, not to glean information about the spectrum being recorded.

In addition to the Info fields, Genie 2000 also has a suite of spectrum analysis tools under the "Analyze" menu. These tools can be used for a variety of different purposes, including peak location, peak area computation, and nuclide identification. The peak location tools "Unidentified 2nd Difference" and "VMS Standard Peak Search," along with the peak area tool "Sum / Non-Linear Least Squares Fit" are the ones used for this thesis. According to Canberra, the Unidentified 2nd Difference algorithm "uses a modified 2nd difference computation over a user specified range of channels," while the VMS Standard Peak Search also uses the 2nd difference method but then fits the peaks using a "pure Gaussian fit routine." (Mirion Technologies, Inc., 2016) There is also an "Execute Sequence" submenu which contains tools that will automatically use several tools in sequence in order to produce results. The one algorithm here used in this thesis is "NID Analysis w/Report." This sequence, when analyzing an efficiency and energy calibrated spectrum will attempt to determine what nuclides are present and in what amount.

The other programs in Genie 2000 employed for this project are the MCA Input Definition Editor, the MID Setup Wizard, and the Nuclide Library Editor. The first two programs are instrumental in creating the MID files which allow the Gamma Acquisition and Analysis program to connect to the MCAs used in each experiment. The MID Setup Wizard program allows for streamlined creation of MID files. The "Editor" program allows users to manually create new MID files and edit existing ones, although the process of creating new ones is not as streamlined as it is in the MID Setup Wizard. Ideally, students should not deal with these programs directly, but they are required for instructors to set up the experiments. Among other settings, the MID files set the bounds on a detector's high voltage, and tampering with the settings can lead to unsafe operation and potential equipment damage. These programs should only be handled by the individuals running the lab and the MID files should be created in advance for students. There are also some cases, such as with the Falcon 5000 portable HPGe detector, where a MID file is supplied by Canberra. The Nuclide Library Editor is used to create custom nuclide libraries for use in Genie 2000. These libraries define what Genie 2000 recognizes as nuclides, including the energy lines it looks for. Libraries can be entirely defined by hand, composed of nuclides taken from other libraries, or a combination of the two.

3.3 LabVIEW

In order to physically manipulate the elements of each experiment, LabVIEW System Design Software from National Instruments was employed. LabVIEW can be used for a wide variety of laboratory functions, but in this thesis it was used for motion control. Using LabVIEW's SoftMotion module, the stepper motors detailed in the next section can be controlled.   LabVIEW functions primarily through the use of its VIs, which are custom-made programs created through the LabVIEW API. National Instruments describes VIs as "LabVIEW programs that imitate physical instruments (National Instruments, 2015)." Each VI consists of a block diagram and a front panel; the block diagram is a visual programming environment, while the front panel is what the end user (i.e. students) interact with in order to use the program. A block diagram is shown in Figure 2, while the corresponding front panel is shown in Figure 3.

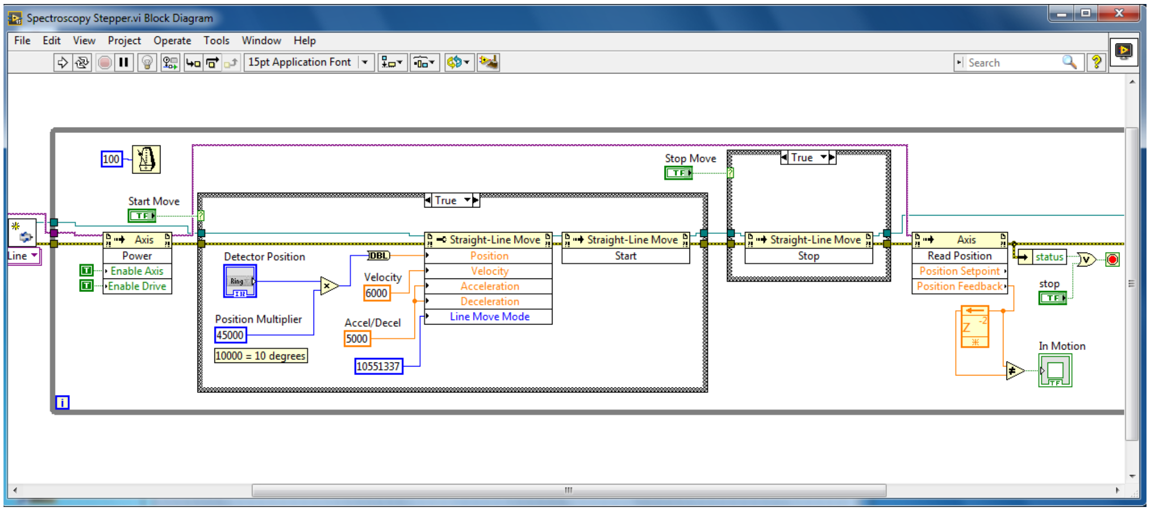
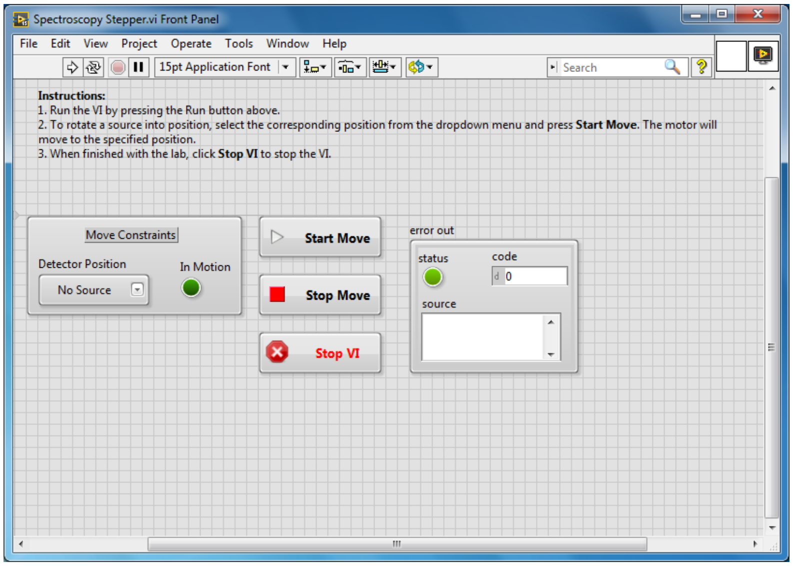


Figure 2 – Block diagram for a LabVIEW VI.



Instructions:
1. Run the VI by pressing the Run button above.
2. To rotate a source into position, select the corresponding position from the dropdown menu and press **Start Move**. The motor will move to the specified position.
3. When finished with the lab, click **Stop VI** to stop the VI.

Figure 3 – Front panel for a LabVIEW VI.

Designing a LabVIEW VI is relatively simple compared to typical programming endeavors. Little knowledge of conventional programming languages and structures a needed. A user interface is assembled on a front panel by adding various elements, including buttons, switches, displays, dialog boxes, lights, and many more. Each of these objects (that are not strictly decorative) can be either a control or an indicator. A control is an object that the user determines the state or value of when the VI is running, such as switches, knobs, or text entry fields. These supply the user’s inputs to the block diagram. In the front panel shown in Figure 3, the menu labeled “Detector Position” is a control, as are the three buttons in the middle labeled “Start Move,” “Stop Move” and Stop VI.” An indicator is an object that the user cannot directly change the state of, rather they display some output of the block diagram. These typically take the appearance of lights, graphs, or text outputs (National Instruments, 2017). The front panel in Figure 3 has two green circles on it, which are indicator lights. The text fields under “error out” displays text outputs that provide information in the event that the VI encounters a problem of some sort.

For every element placed on the front panel, whether a control or indicator, a corresponding terminal is created on the block diagram. For example, the blue square on the left in Figure 2 labeled “Detector Position” corresponds to the menu control with the same name on the front panel. The green square on the right labeled “In Motion” also corresponds to the indicator light with the same name on the front panel. The block diagram is where most of the programming work takes place, and appears akin to a flowchart. Terminals are the inputs and outputs for the block diagram, and the block diagram performs actions based on its inputs and commands the outputs. The block diagram introduces a third type of terminal as well: the constant. Constants are much like controls, except that they do not have a partner on the front panel; constants can only be set in the block diagram. These are used for any aspects of the VI that the designer does not want the user to be able to readily change. Aside from terminals, there are a vast amount of “nodes” that can be placed in the block diagram which allows the VI to perform whatever function the designer wishes it to. Nodes include flow statements such as “while” and “for” loops, functions that take inputs and produce a corresponding output, and even other VIs. These nodes and the connections between them will make up most of the block diagram.

During execution of a VI, each node will execute once it receives all of its required inputs, and will subsequently pass its data to all nodes connected to its output (National Instruments, 2017). Since data flow starts from the controls and constants, program execution starts from those and moves to the immediately dependent nodes, then to the nodes dependent on those, and so on. The VI shown in Figure 2 and Figure 3 is used in the gamma spectroscopy experiment in this thesis, and the block diagram has been split up into Figure 4 and Figure 5 to help describe the process.

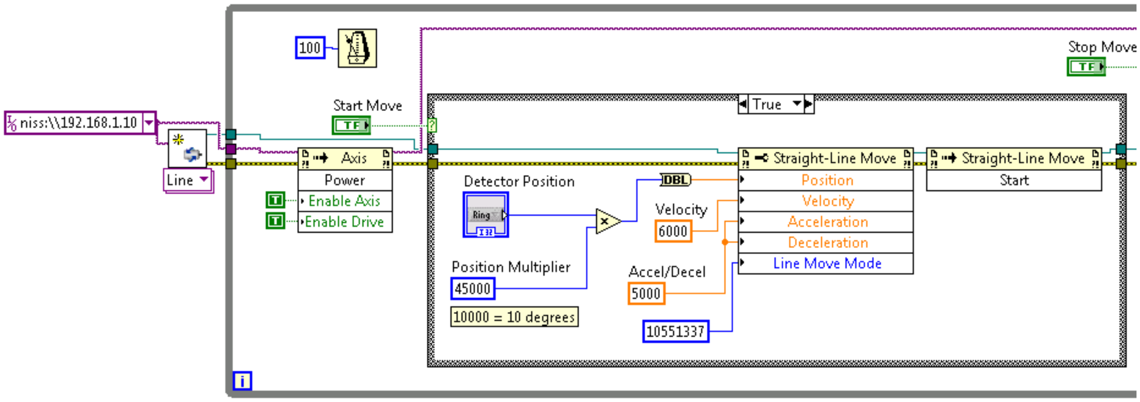


Figure 4 – Part 1 of the rotary table VI used in the gamma spectroscopy experiment.

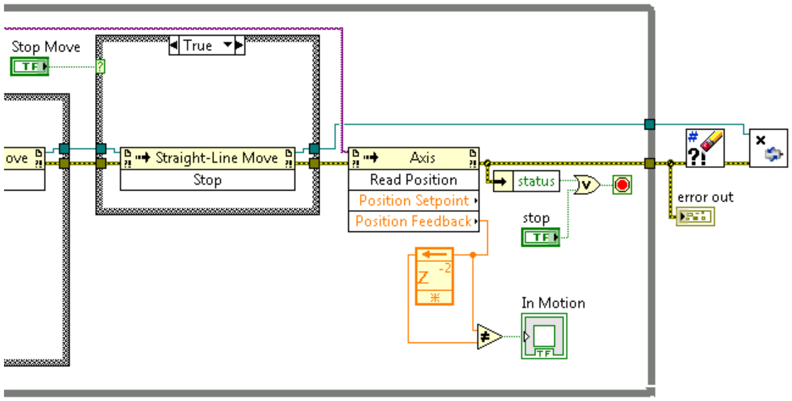


Figure 5 - Part 2 of the rotary table VI used in the gamma spectroscopy experiment.

When executing the VI, computation begins on the left in Figure 4. This is not because it is the leftmost part of the program (although VIs are commonly designed to flow from left to right for ease of use), but because that is where the first node is that has all its inputs fulfilled. In this case, it is the node labeled “Line” which connects the motor for the rotary table to the VI when supplied with the motor’s network address from the connected constant. The program process then enters a large box that defines the apparatus’s movement. This box is a while loop, meaning that whenever execution reaches the end of the box, it will return back where it entered the box. Also note the numeric constant “100” connected to a metronome node in the upper left corner of the loop. These nodes cause the while loop to wait until 100 milliseconds have passed before restarting, with the duration of the delay being set by the “100” constant.

On entering the loop, the first step in the sequence initiates the motor in the “Axis” node. Since the “Enable Axis” and “Enable Drive” options are both set to true by constants and cannot be disabled by the user, they will never change and the motor will always be enabled. This node could be placed before entering the loop without changing how the program works.

With the motor enabled, the program process then encounters the first of two true/false case structures, which are the two boxes inside the while loop with a “True” on the top of them. One is in Figure 4, while the other is in Figure 5. These structures cause different nodes to be executed depending on whether they are supplied a true or false signal from the controls connected to them. In this VI, both case structures contain no nodes for the false case (not shown). If their corresponding controls are false (off) the program will progress past both cases without doing anything. The first case is controlled by the “Start Move” button control. When the button is pressed by the user, that control becomes true (on) for as long as the button is pressed, and the structure switches to the true case.

With the true case, the program reaches the Straight-Line Move command node, also seen in Figure 4. This command will give the motor a complete set of instructions to make a move to the specified point. The user has set a position on the “Detector Position” menu, and each position in that menu corresponds to an integer, starting at 0 and increasing by 1 for every position. That integer is then multiplied by a constant to turn it into a position for the motor. In this VI, 10000 units on the motor corresponds to ten degrees on the rotary table, so by making the position multiplier 45000, each subsequent integer on the position menu corresponds to another 45 degrees on the rotary table. Note that the box labeled “10000 = 10 degrees” does not define how the units correspond to a real life rotation; that box is simply a comment to serve as a reminder for the programmer, as the motor's units are determined by the hardware. With the position determined, two more constants supply the velocity and acceleration & deceleration values for the move. These values are in unknown units, and were chosen because they allowed for adequate movement of the rotary table. The final value required is a code supplied to the Line Move Mode option. This is a code that determines how the Straight-Line Move node interprets a position input. In the mode used in this thesis, the position is treated as absolute; a given position input corresponds to a specific end position for the motor. This is opposed to the other major mode of operation, where the position input is interpreted as being relative to the motor's current position. It is important to use the absolute mode, to ensure that the motor will always rotate to the desired positions.

Immediately after giving the motor instructions for a move, the next Straight-Line Move node commands the motor to start its move. Once this command is given, the motor needs no further instructions from the VI in order to complete its move, so it does not matter if this case structure returns to its empty "false" version (as is the case when the user releases the Start Move button). Moving on to Figure 5, the second case structure contains a Straight-Line Move node with a "Stop" command. This command is not necessary to make the motor stop once it has reached its destination, as it will do that on its own. As with the case structure before it, this structure will only use the true version containing the node when the connected button control ("Stop Move" in this case) is pressed. This button is used to stop the motor's motion prematurely. When

“Stop Move” is pressed, this “Stop” command will be sent to the motor, and the motor will cease its movement.

After passing through both case structures, the program then encounters an Axis node that checks the position of the motor. This position is output through Position Feedback, and is sent to a feedback node. The feedback node saves inputs across loops, and here it is used to compare the position of the motor to its position from two loops ago. If the two positions are not the same, the “In Motion” indicator light on the front panel will illuminate. Lastly, the program moves to a status check. If the motor has encountered an error of if the user has pressed the “Stop VI” button on the front panel, the VI will end the while loop, display an error message (if applicable), and stop the VI. If this is not the case, the program returns to the beginning of the while loop. Unlike the case structures, the Axis node and the status check will be executed every loop, as they do not rely on a user input to be evaluated by the VI.

In summary, when the VI is started, it connects to the motor and enables it. The VI will run through the while loop doing nothing except reading the motor’s position until the user presses any of the buttons. Once the user presses the “Start Move” button, the VI commands the motor to make a move given the current position setting supplied by the user, then goes back to doing nothing but reading the position while the motor makes its move. At any point the user may press the “Stop Move” button to cause the VI to interrupt the motor’s move, or the “Stop VI” button to stop the entire VI. While this is just the VI used for the gamma spectroscopy experiment, the VIs used for the other experiments in this thesis are very similar, only differing in how the position input is evaluated and the address of the motors.

LabVIEW offers a variety of example programs that can be used as starting points for whatever application a user may have in mind. Indeed, one of the highlights of LabVIEW is the wealth of premade VIs that can either be included in another VI or modified for a client's purposes. These example VIs can be found in the LabVIEW installation directory, under "LabVIEW 2015\examples," and the VIs most relevant to this thesis are in the "motion" folder contained within. In this thesis, an Axis Move VI was used as the basis for all of the motor control VIs that were employed to manipulate the Ethernet stepper motors. The example VI was heavily modified to fit the needs of each experiment for this work. In designing the VIs for this thesis, the guiding principle was that they needed to be as simple to operate as possible. It should be intuitive to the user how to operate each VI, and there should be as few potential sources of errors as possible. As a result, the VIs designed for this work were significantly edited to offer fewer options and settings to the end user compared to typical VIs. Most of the existing controls were converted into constants, while new sets of controls were introduced to allow students to control the VIs within the desired limits. For example, in the VI designed for the rotary table, all that is expected of the user is to pick a predetermined position and confirm movement. Settings such as the motor's IP address, movement velocity, and acceleration are already set and hidden from students.

3.4 Ethernet Stepper Motors

The motor elements of the lab are the Ethernet Integrated Stepper Motors, also produced by of National Instruments (ISM-7411E). These are NEMA 23 size stepper motors controlled through an Ethernet connection. These stepper motors offer a few features that make them the motors of choice for this work. First, as these are National Instruments motors, connecting them to LabVIEW is uncomplicated as they are intended to be compatible with this program. Second, being Ethernet-capable, there is no need to complicate the system with motor drivers. They can be connected via LAN connection to the host computer and controlled by LabVIEW directly instead of having to use an additional piece of equipment to connect the devices. Third, the specific model used comes with an encoder. The important consequence of this is that the motor always "remembers" where it is; even if a VI is shut down or if the host computer itself is restarted, the motor will save its position. Only a loss of power to the motor will cause it to forget its location. This is an essential feature in preventing a loss of synchronization. Without it, it is possible that positions of lab elements could be incorrect, leading to incorrect motor positions or potentially running the linear slide off its rail.

3.5 Rotary Table

The first of the two motor-controlled elements is the rotary table. This part, shown in Figure 6, is a Velmex B4818TS Rotary Table (Velmex, Inc., 2016). A rotary table allows for simple repositioning of lab elements, useful for things like selecting sources. This rotary table also has NEMA 23 sized couplings, so as to properly connect to the stepper motors.

This particular rotary table was chosen due to its reliability and durable construction. This being a radiation detection lab, it was a reasonable expectation that lead shielding would be employed on the table at some point. Thus, a rotary table with a high weight capacity was desired, and the Velmex B4800TS series rotary table met that criterion with a 200 lb. weight limit.

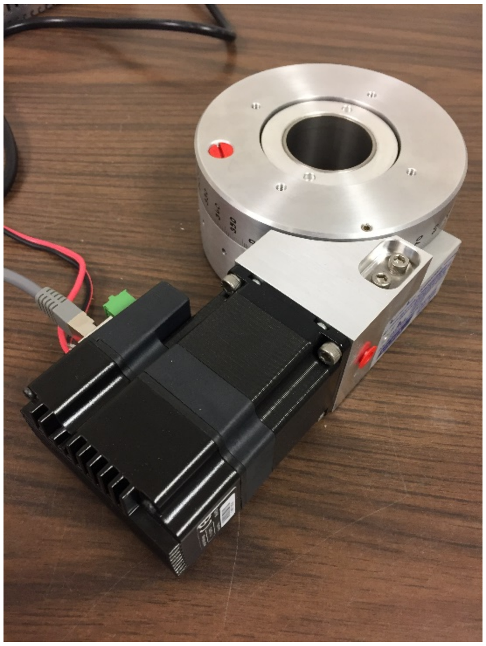


Figure 6 – Rotary table coupled with one of the stepper motors, both size NEMA 23.

3.6 Linear Slide

The second motor-controlled element is the linear slide. This part, shown in Figure 7, is a 36 inch LinTech 140 Series Belt Driven Linear Actuator (LinTech Motion Control, Inc., 2017). The linear slide allows for linear movement, useful for repositioning components and, for example, altering the distance between a source and detector. As with the prior parts, the linear slide also accepts a NEMA 23 size motor.

This linear slide was chosen for its flexibility and affordability. Since the amount of weight this apparatus would need to carry are far lower than that for the rotary table (as there is no real need to place more than a single block of lead on it) a more lightweight and less costly model was desired. When using this component, it is important that one does not drive the platform too far to one end or the other. Attempting to drive the platform beyond its end bounds could cause damage to the device. Therefore it is important to design the LabVIEW programs such that a student cannot accidentally drive the platform too far, this being another reason why it is important that the stepper motors have encoders on them.

Figure 7 – Linear slide coupled with one of the stepper motors.

3.7 Camera

The final part of the system is a camera and is more of a convenience for the student than a necessity. This camera allows the student visual feedback when moving lab apparatuses. The camera used was a Logitech C270 webcam. Students can open the camera application on the host computer in order to see the experiment taking place and receive visual confirmation that lab elements have moved as expected. It is important to note that the camera must be prepositioned by those managing the laboratory so that the experiment may be completely seen by the remote student. It is recommended that students use the camera in its lowest resolution mode to ease the strain on the remote desktop connection. This still allows for ample viewing of the lab.

4. EXPERIMENTS

4.1 Gamma Source Identification

The first experiment setup for the remote laboratory was for gamma source identification. When this experiment is assembled, students are supplied with a selection of common gamma check sources laid out on the rotary table. A NaI scintillation detector is attached to a Canberra Osprey MCA, which is in turn connected to the host computer. The detector is situated above one corner of the rotary table and shielded from the rest of the table with lead blocks. A picture of the setup is shown in Figure 8, and a full procedure for this lab can be found in Appendix A.

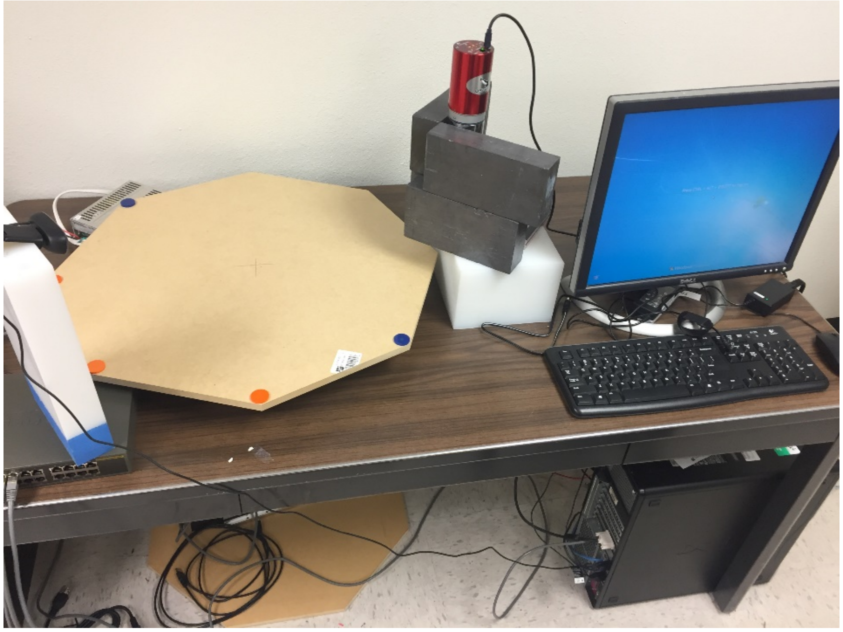


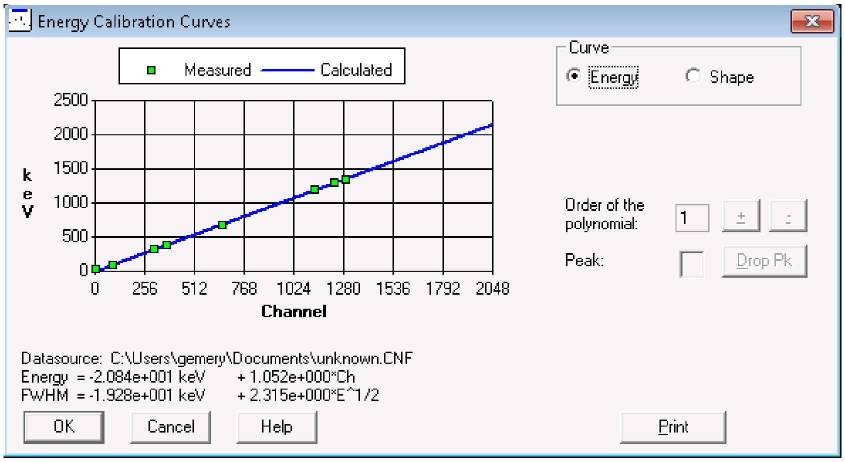
Figure 8 – The setup for the gamma source identification lab.

The goal of this experiment is to familiarize the student with Genie 2000 and common scintillation detectors. Students must start Genie 2000 and load the detector, apply the high voltage, and then use a set of check sources to calibrate the MCA. Switching between sources is accomplished by the use of a LabVIEW VI (Spectroscopy Stepper.vi) which controls the rotary table. The VI lists positions, not sources. The experimental procedure for the students will list which source is in which position, so teachers can assign sources as they see fit. To choose a source, students need only select its position and confirm. The rotary table then moves the selected source into position under the detector. During the calibration procedure, students are directed to record the energy, centroid channel, area and uncertainty of each of the photon peaks. Once the energy calibration is completed, students then select an “unknown” source. The student identifies the unknown radionuclide by determining the energy of each peak present in the calibrated spectrum.

Much of this lab revolves around the energy calibration of the NaI detector. In order to perform an energy calibration, it is necessary to have known radiation sources, preferably with photon emissions that are both high in abundance and with energies spread throughout the recorded spectrum. For this laboratory the sources used were ^{137}Cs (662 keV), ^{60}Co (1173 and 1332 keV), ^{22}Na (511 and 1274 keV) and ^{133}Ba (80 to 300 keV). The peaks in the spectrum produced by each source can be linked to the known energy for their corresponding photon emissions. By doing this for multiple sources to get photon energies all along the MCA’s spectrum, an energy calibration curve can be determined, making every channel accurately correspond to some radiation energy. This also influenced the choice of radiation sources in this lab; ^{137}Cs is a popular mid-range source, ^{60}Co and ^{22}Na have their gammas at higher energies over 1

MeV, and ^{133}Ba has many gamma decays in the lower energy ranges from 80 keV to 300 keV.

Genie 2000 makes the process of calibration significantly easier for the user, simplifying the entry of calibration data points and applying the calibration to the spectrum automatically. In the “Energy Only Calibration” tool, the user enters the energy of a gamma peak and the corresponding channel. As this option estimates the FWHM and does not utilize nuclide libraries, this is only recommended for an initial, rough calibration in order to make further refinement of the calibration easier. In the “Energy Calibration By Nuclide” option, the nuclide being counted can be chosen, and the user can either have Genie 2000 automatically fill in the channels for the nuclide’s peaks or fill it in by selecting the peaks by hand. The user can only use the automatic option if at least a rough calibration has been performed, or Genie 2000 will not be able to locate the appropriate peaks. At any point, the calibration curve being used can be examined with the “Energy Show” option. An example Genie 2000 calibration curve from this experiment can be seen in Figure 9.



```
Datasource:  C:\Users\gemery\Documents\unknown.CNF
Energy  = -2.084e+001 keV      + 1.052e+000*Ch
FWHM  = -1.928e+001 keV      + 2.315e+000*E^1/2
```

Figure 9 – The calibration curve produced in the gamma identification experiment.

A trial run of this experiment was conducted remotely. The host computer was connected to from offsite and the camera software, Genie 2000, and the "Spectroscopy Stepper" VI were started. The Canberra Osprey MCA was loaded into Genie 2000 and the detector was biased with 800 V. The first step in this experiment was to set the "scale" of the spectrum (the maximum energy associated with the last channel in the spectrum) to 2 MeV and to start calibration. A ^{137}Cs check source was used for this due to its prominent gamma peak at 662 keV. The Spectroscopy Stepper VI was used to rotate the ^{137}Cs source into position and the source was counted. During acquisition, the gain of the detector was adjusted until the peak from ^{137}Cs fell close to a certain channel. Since the Osprey MCA provided 2048 channels and a 2 MeV spectrum was desired, 662 keV out of 2 MeV corresponds to channel 678 out of the 2048, so 678 was the target channel. This was calculated using Equation 1.

$$\mathrm{C_{Cs}} = \frac{\mathrm{E_{Cs}} * C_S}{\mathrm{E_S}} = \frac{662\ \mathrm{keV} * 2048}{2000\ \mathrm{keV}} \qquad \text{Eq. 1}$$

Where:

E_{Cs} is the known energy of the ^{137}Cs peak (662 keV);

E_S is the desired maximum energy of the spectrum (2000 keV);

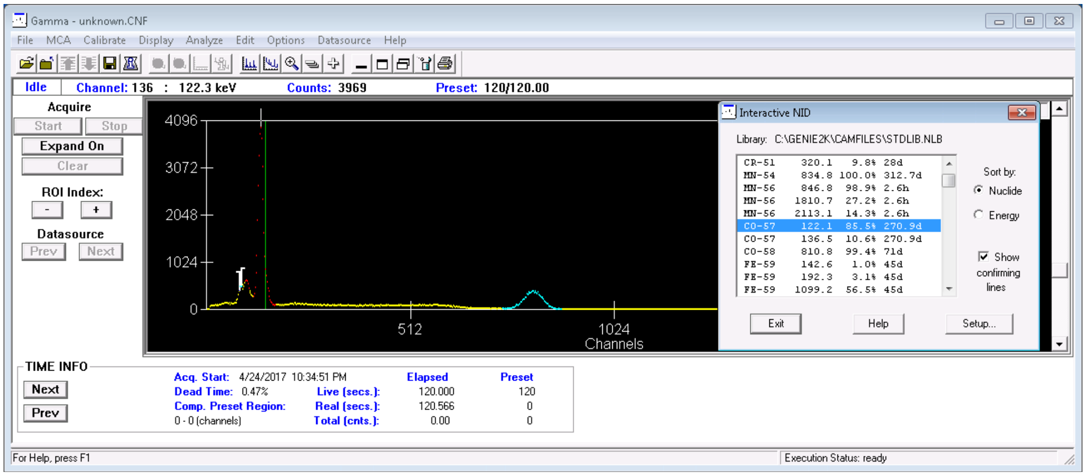
C_S is the maximum channel number of the spectrum (2048);

C_{Cs} is the target channel for the ^{137}Cs peak.

Once the gain was set for a 2 MeV spectrum a 180 second spectrum was acquired so that spectral features such as the Compton Edge and backscatter peak could be observed and recorded by the student. In addition, the Energy Only calibration tool was used to start the calibration process with a rough calibration. The spectrum was saved and the experiment was continued.

The VI was used to rotate the next source, ^{60}Co, into position in front of the detector. This source was also counted for 180 seconds. After counting, the Energy By Nuclide List calibration tool was used to add the ^{60}Co peaks at 1173 keV and 1333 keV. The spectrum was saved. This process was repeated for ^{22}Na and ^{133}Ba, though the 511 keV peak produced by positron annihilation from ^{22}Na was not utilized in the calibration. The final calibration curve produced was the one depicted in Figure 9. With the calibration complete, the VI was used to rotate the last sources into position. These sources were the “unknowns,” with the goal being to identify them without looking at their labels. These sources were also counted for 180 seconds.

In order to identify the sources, the Interactive NID tool in Genie 2000 was employed. A picture of the Interactive NID in use can be seen in Figure 10. The Interactive NID tool uses a Genie 2000 nuclide library to provide a list of nuclides. The library lists isotopes, associated photon emissions, photon yield, and the nuclide’s half-life. The user can sort this list by nuclide or by energy. When selecting any specific gamma in the list, the Gamma Acquisition and Analysis program moves the spectrum cursor to that energy. Conversely, moving the cursor to a channel will cause the program to display any known gammas at that channel’s energy. Whenever a gamma is selected, the user has the option to "Show confirming lines," which displays the locations in the spectrum of all other gammas from that nuclide. Therefore this tool allows for quick selection and elimination of possible nuclides for a given peak in the spectrum; if a peak could correspond to some nuclide, but none of the other peaks from that nuclide appear, that nuclide can be rejected. The half-life and abundance information can also be used to reject nuclides too short-lived or with abundances too small to be possible.



Idle Channel: 136 : 122.3 keV Counts: 3969 Preset: 120/120.00

Library: C:\GENIE2K\CAMFILES\STDLIB.NLB

```
CR-51     320.1   9.8% 28d
MN-54     834.8 100.0% 312.7d
MN-56     846.8  98.9% 2.6h
MN-56    1810.7  27.2% 2.6h
MN-56    2113.1  14.3% 2.6h
CO-57     122.1  85.5% 270.9d
CO-57     136.5  10.6% 270.9d
CO-58     810.8  99.4% 71d
FE-59     142.6   1.0% 45d
FE-59     192.3   3.1% 45d
FE-59    1099.2  56.5% 45d
```

Acq. Start: 4/24/2017 10:34:51 PM
Dead Time: 0.47%
Comp. Preset Region:
0 - 0 (channels)

	Elapsed	Preset
Live (secs.):	120.000	120
Real (secs.):	120.566	0
Total (cnts.):	0.00	0

Execution Status: ready

Figure 10 – The interface for the Interactive NID. The vertical green line in the spectrum is one of its confirming lines.

The unknown sources were able to be successfully identified; the sources were ^{57}Co and ^{54}Mn, and analysis of the spectrum's peaks gave gamma energies within 1 keV of the expected values. From the energies of the peaks in the spectrum, it was possible to identify the unknown sources by comparing them to known gamma radiation energies in conjunction with eliminating unreasonable isotopes with similar gamma energies.

There were a few complications involved in the construction and execution of this experiment. The observed peaks were difficult to resolve in Genie 2000, which could be due to a number of reasons. One candidate is a flawed detector. If a detector's crystal is damaged in some way, this can lead to a loss of resolution, causing the recorded peaks to widen. A damaged crystal may even split a photopeak, causing two almost indistinguishable peaks to be recorded. Another possible issue may be in the Genie 2000 software itself. The algorithms it uses to identify and quantify spectral features are designed around use with high-quality (HPGe) spectra and, while they can certainly be used for lower resolution spectra, they are less successful.

4.2 Uranium Enrichment Quantification

The second experiment created for the remote laboratory was a uranium enrichment quantification experiment. Here, several uranium samples of varying enrichment levels were placed on the rotary table, along with several gamma check sources. A portable Canberra Falcon 5000 HPGe detector was connected to the host computer. The detector was situated off to one side of the rotary table and was shielded from the samples with lead blocks. Lead was also placed on the table to reduce spectral interference from other sources on the table. As with the previous experiment, switching between sources was accomplished via a LabVIEW VI to control the rotary table's position. A picture of the experiment setup is shown in Figure 11. A full procedure for this lab can be found in Appendix A.

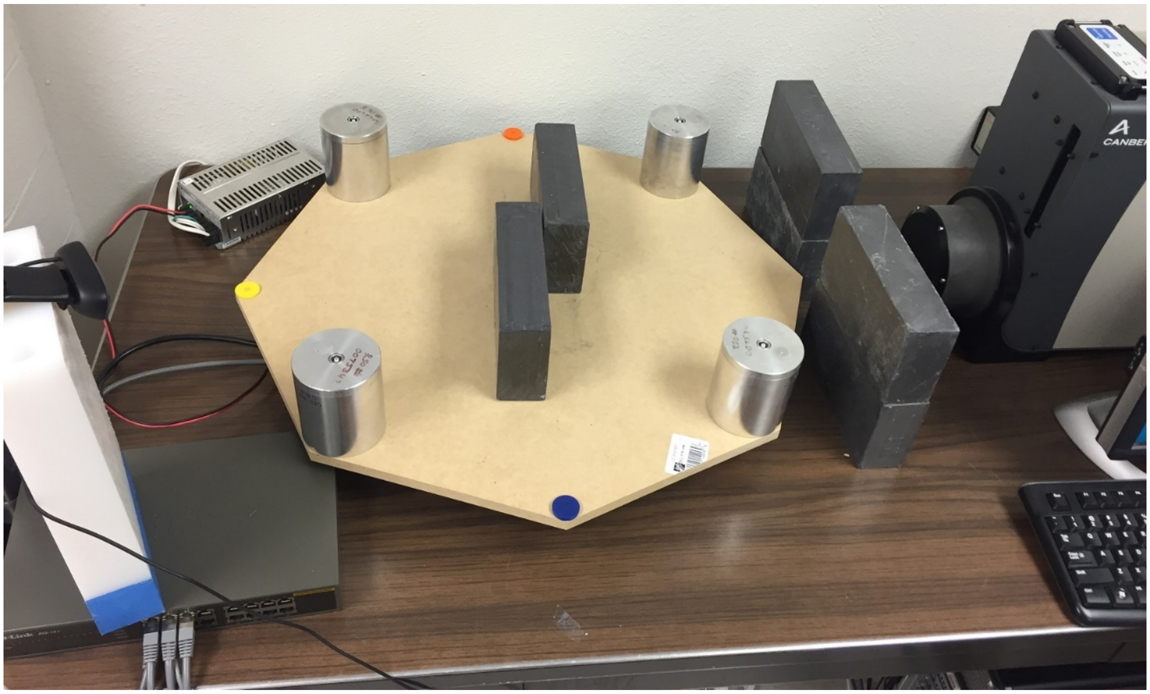


Figure 11 – The setup for the uranium enrichment quantification experiment.

In this experiment, the goal was to provide students experience working with HPGe detectors and to conduct uranium enrichment measurements from gamma radiation measurements. In the first half of the lab, students activated the HPGe detector and performed both energy and efficiency calibration using ^{137}Cs and ^{152}Eu. They then used their calibration to identify and quantify an unknown source. Once the system was calibrated, students collected a spectrum of a uranium source of known enrichment, followed by collecting the spectra of unknown uranium sources with unknown enrichments. Students then used the simple comparator method to determine the enrichments of the uranium sample (Marianno, Lecture 7: Gamma Ray Spectroscopy with Semiconductor Detectors, 2016). This method, shown in Equation 2, allows for a quick estimation of the enrichment of unknown uranium samples given a known sample.

For each measurement it is assumed that the size, distribution, container properties and position of the uranium samples are all the same, or the equation will not hold.

$$\frac{\left[\frac{C_{k,235}}{C_{k,238}}\right]}{\left[\frac{C_{unk,235}}{C_{unk,238}}\right]} = \frac{\left[\frac{A_{k,235}}{A_{k,238}}\right]}{\left[\frac{A_{unk,235}}{A_{unk,238}}\right]} \qquad \text{Eq. 2}$$

Where:

$C_{k,235}/C_{k,238}$ is the ratio of counts in the ^{235}U 186 keV peak compared to counts in the 1001 keV associated with ^{238}U for the known source;

$C_{unk,235}/C_{unk,238}$ is the ratio of counts in the ^{235}U 186 keV peak compared to counts in the 1001 keV associated with ^{238}U for the unknown source;

$A_{k,235}/A_{k,238}$ is the estimate of the known source enrichment;

$A_{unk,235}/A_{unk,238}$ is the estimate of the unknown source enrichment.

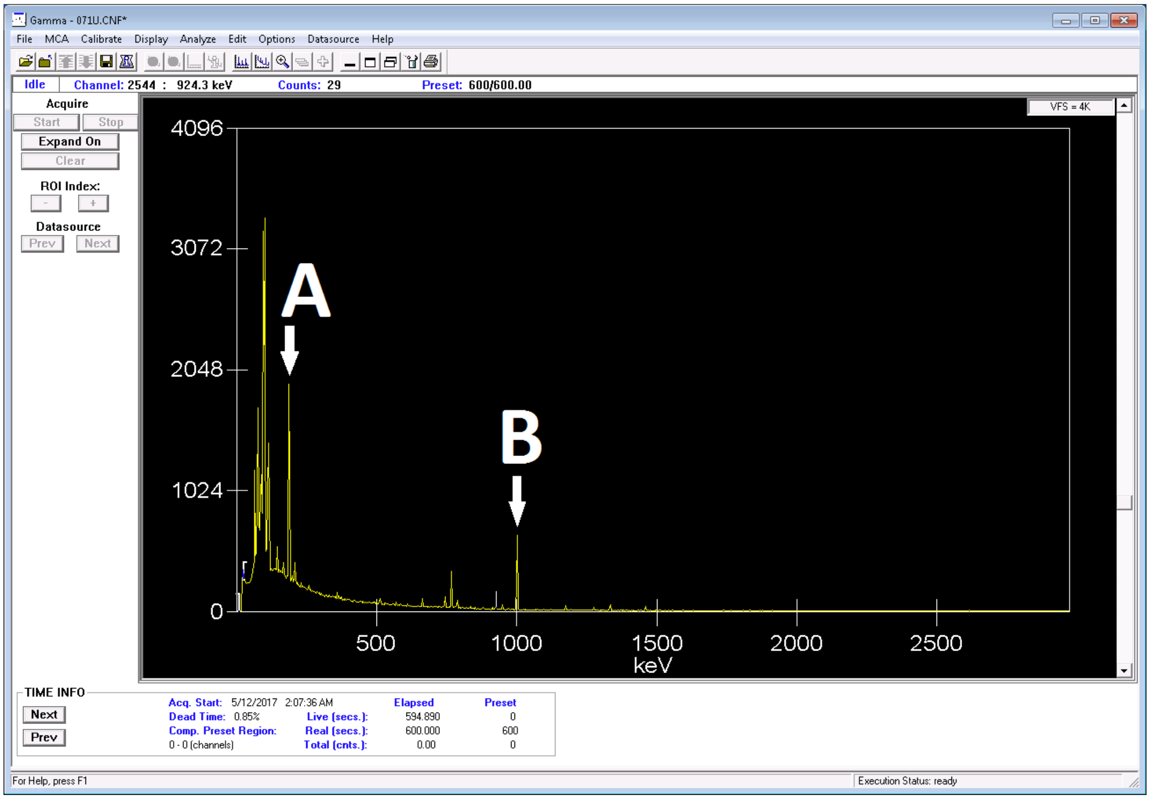
By carefully counting both the known and unknown uranium samples the ratio of counts of ^{235}U to ^{238}U can be found for each sample. The activity ratio of ^{235}U to ^{238}U in the unknown uranium sample (i.e. its enrichment) can then be solved for. While ^{238}U cannot be directly detected via gamma ray detection as its gamma emissions are all low-energy (the largest is at 113 keV) and it has a very long half-life, it is in secular equilibrium with one of the products in its decay chain: ^{234m}Pa. When this product decays it emits a gamma ray at 1001 keV, although the abundance of this gamma ray is low at around 0.84% (National Nuclear Data Center, 2007). This will still be sufficient for the method as it is the ratio that is important, and the quantity of ^{234m}Pa is directly proportional to the quantity of ^{238}U.

After remotely logging into the computer system the students use different components of the Genie software package. First, they are directed to create a custom nuclide library using the Genie Library Editor. To simplify analysis, the library only contains the nuclides used in this experiment (^{137}Cs, ^{152}Eu, ^{235}U, and ^{238}U) and excludes all other sources. This nuclide library should be used for this experiment in lieu of the standard nuclide library used by Genie 2000.

Once the library was created the student calibrates the detector, then identifies and quantifies an unknown source. The apparatus is manipulated using the LabVIEW Uranium Stepper VI created for this experiment. As before, the Gamma Acquisition and Analysis software was used to operate the detector and record data. In Genie 2000, the MID file corresponding to the Falcon 5000 detector was loaded, and the bias voltage was set to 3000 V and turned on. The VI was used to rotate the first source, ^{137}Cs, into position in front of the detector. The source was first used to set the gain of the detector to a spectrum range of 3 MeV. Following the technique presented in the previous experiment, the 662 keV peak was placed in channel 1808 of the 8192 channel spectrum. After setting the gain, a 180 second count of the ^{137}Cs source was taken, and the spectrum was used to begin the energy calibration of the detector.

The VI was used to rotate the next source into position: ^{152}Eu. The source was counted for 300 seconds, and the spectrum was used to fill out the energy calibration of the detector further. In addition, the ^{152}Eu spectrum was used to calibrate the detector's efficiency as well. With the known assay date and activity of the source, Genie 2000 was used to create an efficiency calibration for the detector. In order to verify the calibration of the Falcon 5000, the VI was used to rotate an “unknown” check source into position. Using Genie 2000’s NID Analysis function, the source was successfully identified as ^{133}Ba.

The next section of the experiment focused on uranium enrichment determination. During setup four uranium sources ranging in enrichment from 0.31% to 4.2% were positioned on the rotary table, along with the check sources (Figure 11). A natural uranium source, with 0.71% ^{235}U enrichment, was the only uranium source of the four whose enrichment would be provided to students. The ultimate goal of this section of the lab was to count the uranium sources and then use the collected data to determine the enrichment of the unknown uranium sources. Each of the uranium sources, starting with natural uranium, were counted for 10 minutes each, using the VI to switch between samples. An example spectrum of the natural uranium source is shown in Figure 12. Genie 2000 was used to perform an Unidentified 2nd Differential peak search to determine ROIs for the 186 keV and 1001 keV peaks. This gave the counts and the uncertainty in the counts for each peak of concern in the spectrum.



Idle Channel: 2544 : 924.3 keV Counts: 29 Preset: 600/600.00

		Elapsed	Preset
Acq. Start: 5/12/2017 2:07:36 AM			
Dead Time: 0.85%	Live (secs.):	594.890	0
Comp. Preset Region:	Real (secs.):	600.000	600
0 - 0 (channels)	Total (cnts.):	0.00	0

Execution Status: ready

Figure 12 – The radiation spectrum from the natural uranium source. The peak at A is the 186 keV peak from ^{235}U, while the peak at B is the 1001 keV peak from ^{238}U.

With the counts and corresponding uncertainties for the 186 keV and 1001 keV peaks, the enrichment of the unknown uranium sources could be estimated. For the 0.31% enriched source, the calculations came out to be 0.30% ± 0.02. For the 1.94% enriched source the calculations came out to be 2.06% ± 0.07. While the first unknown sample was determined to within a standard deviation, the second unknown sample was calculated slightly outside of a standard deviation. The experiment was, for the most part, a success, as the experiment was successfully conducted remotely and with tolerable results. Although the simple comparator method utilized in this lab may not be suitable for situations where a high degree of accuracy is paramount, it makes for a quick and relatively simple method of estimating uranium enrichment. It can allow the user to make a quick determination between, for example, natural uranium and LEU. In future experiments, it is likely that the uncertainty could be reduced by increasing count times or improving the geometric efficiency of the detector-source setup, which would in turn give more accurate results.

4.3 GM Dead Time Determination and Statistical Analysis

The final experiment employed a GM tube to explore counting statistics and perform dead time calculations. The purpose of this experiment is to introduce the students to GM tubes and beta radiation detection, as well as have them determine the dead time of the detection instrument. The dead time of a detector is the minimum time that must separate two detection events in order for them to be recorded as two separate pulses. It is an important quantity in radiation detection, as it can heavily influence the recording of a spectrum if caution is not taken. A detector receiving too many counts per second may have a significant amount of the detection time taken up by dead time, which means that much of the radiation that is actually entering the detector is not being recorded. This is detrimental to the spectrum’s statistics and can impede any analysis of efficiency. In addition, students will use this experiment as an opportunity to learn about counting statistics.

This experiment brings the linear slide into play. The GM detector is attached to the linear slide, while one part of a ^{204}Tl split source is attached to the side of the rotary table. The other half of the beta split source is stationary, situated so that the first half can be rotated adjacent to it. This setup is shown in Figure 13; the stationary source is visible on the right side, while the movable source is on the left side.

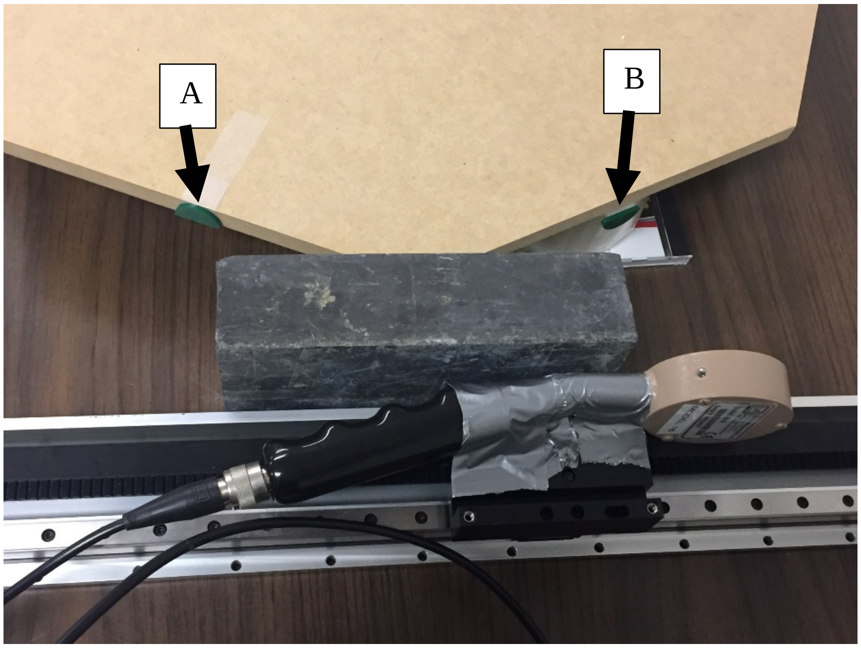


Figure 13 – The split beta source setup for the dead time lab. The source on the left (A) is movable and is affixed to the table, the source on the right (B) is stationary and just below the edge of the table.

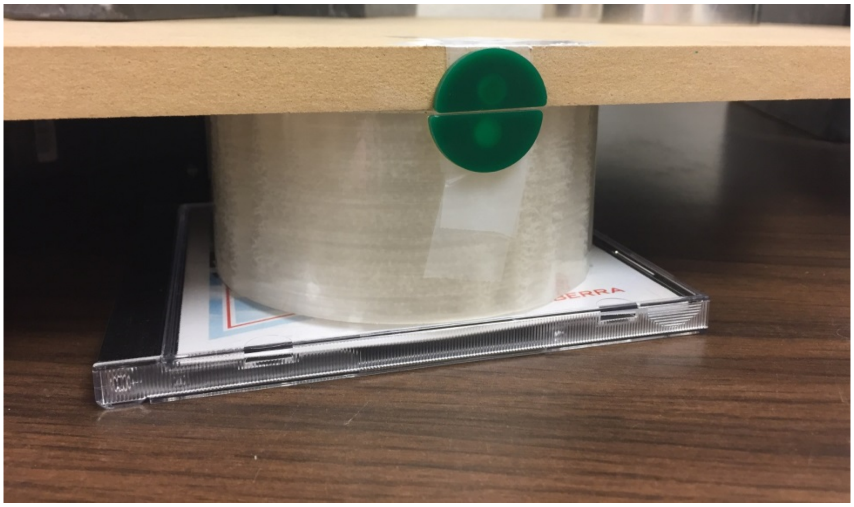
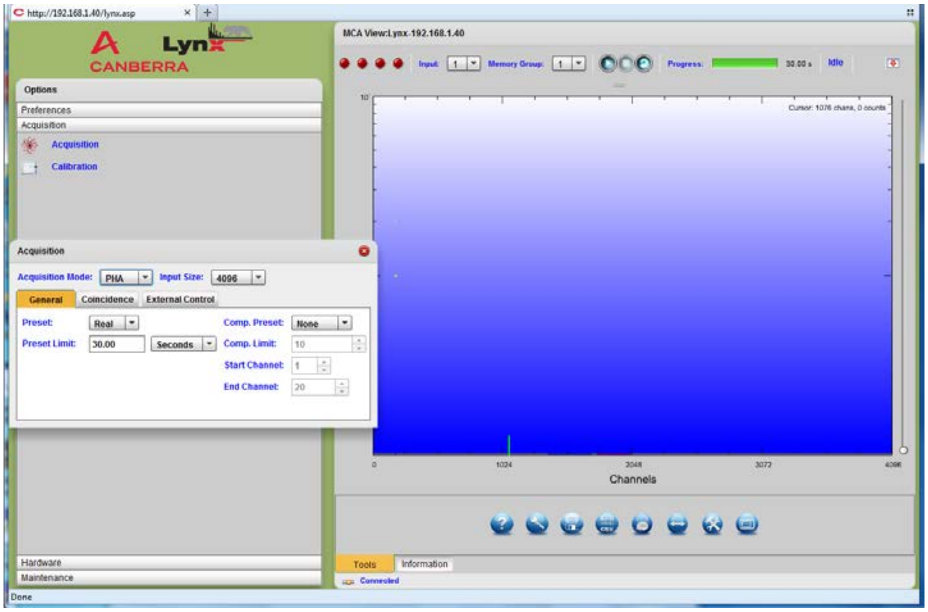


Figure 14 – The alignment of the movable and stationary beta split sources when the movable source is rotated to be adjacent to the stationary source.

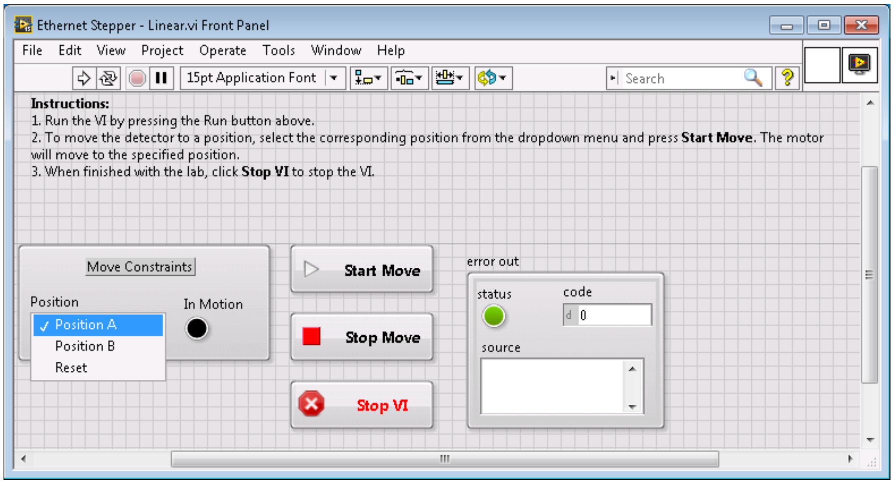
To begin the setup of this experiment, the linear slide is positioned alongside the rotary table. The result is that the GM tube can be moved between two positions with the stationary source at one position, while the source on the rotary table can be moved to either position. Therefore, students can measure either source independently, both at once, or neither. Although the detector is moved between two different positions in this experiment, care was taken to make the detection geometry at the two positions as similar as possible. Shielding material was placed between the two positions to prevent sources at one position from interfering with counts taken at the other. Though lead may be excessive shielding for beta radiation, it was in plentiful supply. A Canberra Lynx MCA was used in this lab to analyze the signal from the GM tube. Unlike in the other experiments in this thesis, the Lynx’s web interface was used instead of Genie 2000. A picture of this interface can be seen in Figure 15. The Lynx was used because of its ability to work with a wide variety of detectors as well as its attenuation feature, which allows it to handle pulses too large for most MCAs, such as those produced by GM tubes.



Acquisition Mode: PHA
Input Size: 4096
Preset: Real
Preset Limit: 30.00 Seconds
Comp. Preset: None
Comp. Limit: 10
Start Channel: 1
End Channel: 20
Input: 1
Memory Group: 1
Progress: 30.00 s

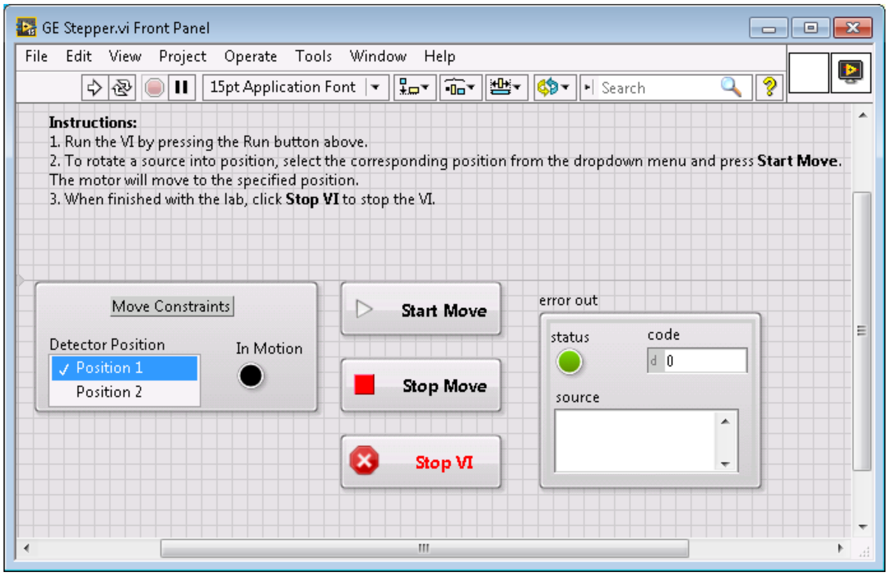
Figure 15 – An example picture of the web interface for the Canberra Lynx MCA.

Students control both the rotary table and the linear slide in this experiment, with two separate LabVIEW VIs controlling each. The rotary table VI is not the same as for the previous labs; to reduce potential confusion, the available positions have been reduced to just the two necessary for the experiment. These VIs are shown in Figure 16 and Figure 17, with the position menus opened. The “Reset” option in the Linear VI moves the detector behind the shielding, Position A moves the detector to the left position away from the stationary source and Position B moves the detector to the right, in front of the stationary source. The rotary table VI has two positions. Position 1 moves the movable source to the left position away from the stationary source, and Position 2 moves the movable source to be adjacent to the stationary source, combining the split source.



Instructions:
1. Run the VI by pressing the Run button above.
2. To move the detector to a position, select the corresponding position from the dropdown menu and press **Start Move**. The motor will move to the specified position.
3. When finished with the lab, click **Stop VI** to stop the VI.

Figure 16 – The front panel of the VI that controls the linear slide in the GM Tube experiment.



Instructions:
1. Run the VI by pressing the Run button above.
2. To rotate a source into position, select the corresponding position from the dropdown menu and press **Start Move**. The motor will move to the specified position.
3. When finished with the lab, click **Stop VI** to stop the VI.

Figure 17 – The front panel of the VI that controls the rotary table in the GM Tube experiment.

Students use the Lynx MCA's web interface instead of Genie 2000 in this experiment. Using one of the halves of the split source, students solve a series of counting statistics problems. First, students take 40 six-second counts of a single half of the ^{204}Tl split source. From this, they are directed to calculate the mean of the population, the residuals of each count, and the standard deviation of the population as well as examining how the set of counts compares to their standard deviation. Ideally, students should see that close to 68% of their counts fall within one standard deviation of the mean value. After that, the goal is to experimentally determine the dead time of the detector. Students take a background count, then count each of the sources independently for 30 seconds each. The rotary table half of the split source is then moved adjacent to the static half, and the two sources are counted together. With the count rate from each source in combination with the count rate from the joined sources, the students calculate the dead time using Equation 3 (Marianno, Lecture 4: Gas-Filled Detectors and General Detector Properties, 2016).

$$\tau = \frac{M_1+M_2-M_{12}}{2M_1M_2} \qquad \text{Eq. 3}$$

Where:

τ = GM probe dead time (s)

M_1 = count rate for half-source 1(s^{-1})

M_2 = count rate for half-source 2 (s^{-1})

M_{12} = count rate for the combined source (s^{-1})

This equation assumes that the detector is non-paralyzable, which means that the detector will not prolong its dead time if radiation enters the detector before it recovers. Dead time will only begin after a successful count is made. This equation is also a simplification of a more accurate and complex equation, which could lead to some higher uncertainty in the calculation. However, since students are only trying to estimate the dead time, and the difference between the two equations should be within an order of magnitude, this equation was seen as acceptable for the purposes of this experiment. Lastly, this equation makes the assumption that background radiation is low compared to the detection events from the source. If the background detection rate was within an order of magnitude as the count rate of the source, the equation which takes the background into consideration should be used. Once the students calculates their instrument's dead time they are directed to compare the value to the manufacturer's stated dead time. A full procedure for this lab can be found in Appendix A.

This experiment was tested by connecting to the host computer from offsite and executing the experiment remotely. The camera program, both of this experiment's LabVIEW VIs, and the Lynx Web application were loaded. The first part of the experiment was finding an operating voltage for the GM tube in the "Geiger" voltage region. In this region, the amount of charge liberated by the incident radiation is constant, regardless of the energy of the radiation. The detector was moved to the stationary source, and the movable source was moved away. Starting with detector voltage at 500 V, the detector was set to record for 18 seconds, and the total counts in the resulting peak were recorded. The voltage was increased by 25 V, and the counting and recording was repeated. This was continued until 950 V. Counts as a function of applied voltage were plotted and the GM plateau was identified. The operating voltage was picked approximately halfway into the plateau at 850 V.

With the GM tube's voltage set, the next part of the experiment was to perform some counting statistics. The detection time was set to six seconds, and a series of 40 counts was taken, recording the total detections for each count. With all of the counts recorded, the mean of the population was calculated, along with all of their residuals (their difference from the mean) and the standard deviation of the population.

The final section of the experiment was to calculate the dead time of the detector. The detector was moved using the VI to Position A where the movable source was. The detection time was set to 30 seconds, and the count time, counts, and count rate were recorded. The detector was moved back to Position B, and this process was repeated for the stationary source. Finally, the rotary table VI was used to move the movable source back together with the stationary source, and both sources were counted at once. The count time, counts, and count rate of the combined sources were also recorded. From these three count rates, the dead time could then be calculated.

In the statistics potion of the experiment, the average of the 40 six second counts was calculated, and the sum of their residuals was zero. The sum of the residuals is expected to be zero as each residual is that count's difference from the mean. If the sum of their differences was not zero, then the mean from which they were derived could not be correct. The standard deviation of the population, as this is assuming a Poisson distribution, was calculated by taking the square root of the mean of the population. When compared to the residuals of the counts, it was found that 55% of the counts fell within one standard deviation. This was less than the expected value of 68%, but it is not entirely unexpected; a population of 40 counts can still have significant differences from an ideal population. With the statistical analysis completed, the next part was the dead time determination. Using Equation 2, the dead time was calculated to be 2.7 ms with an uncertainty of 0.14 ms. This was significantly larger than the manufacturer's stated dead time of 80 μs, and while the short counting times may have contributed some inaccuracy to the results, it is likely there are additional causes for this. While the experiment was successfully conducted, the results of the dead time calculation were poor, and indicate a need for improvements in the experiment.

5. FEEDBACK & CONCLUSIONS

5.1 Feedback

Input was received on how to make improvements to the system for the future. Much of the feedback revolved around connectivity issues. The issue most reported by testers was that when the camera program is opened the connection quality drops dramatically. While the “in motion” lights in the VIs mean the experiments can still be completed, it is rather unfortunate for a student. Alleviating this may require a change in remote desktop software or investigating different methods to use the camera.

Another issue was tied to the system’s resources, specifically what happens if they are not properly relinquished by a user. Should any user of the system fail to properly close their programs when finishing their work, these programs are still considered to be in use by that user even after they log off. This means nobody else can use the programs until they are freed from the first user. This can be accomplished easily by restarting the system, but it is something that needs to be kept in mind. A similar piece of feedback was what it takes to get a student or otherwise to be able to use the remote computer. Each desired user needs to be manually given access by TAMU IT. This can sometimes take an extended period, but it at least adds a level of cyber security.

This is related to another important issue as well. Though it was not encountered during the work of this thesis, it is possible a student could log in to the experiment system and then sabotage it. File permissions need to be set for future implementations of this system to ensure that users cannot edit the files necessary for the system to operate and the software to run. There is also the concern of copyright and export control related issues. It may be possible for a user to copy program files from something like Genie 2000 to their computer, possibly including software under export control restrictions, which could lead to their unwanted transfer to other states.

Improvements need to be made to the GM tube experiment especially. The dead time calculation in the experiment did not perform up to expectations, but this may be remedied. A new experiment setup may make it so that the geometry is shared for both halves of the split source, instead of the current state where they are set up to be as close as possible but are still separate and therefore subject to uncertainty. The program of choice for analyzing the spectral data for the Lynx MCA may be a contributing factor as well. The Lynx web app is not nearly as robust as Genie 2000, and it may be better to perform analysis through Genie 2000 instead.

5.2 Conclusions

Three laboratory experiments were successfully constructed and then executed remotely by connecting to the host computer from off campus. These experiments were made to test the ability of the system to host experiments that could be completed remotely, where the goal of the experiments was to give students experience with radiation detection.

The system was composed of a host computer, a rotary table, a linear slide, and a webcam. The major software suites on the host computer were Canberra’s Genie 2000 and National Instrument’s LabVIEW. Genie 2000 was used to control and read data from connected radiation detectors, while LabVIEW was used to control the rotary table and linear slide. The webcam's bundled software was also used in order to control the camera. The rotary table and linear slide were used to physically manipulate the components of each experiment.

The first of the experiments was the gamma identification lab, in which ^{137}Cs, ^{60}Co, ^{22}Na, and ^{133}Ba were used to calibrate a scintillation detector. With the detector calibrated, it was then used to identify an unknown source(s). This experiment introduces students to gamma spectroscopy, the importance of calibration, and identification of unknown sources.

The next experiment was the uranium enrichment lab. In this lab, students were provided check sources with which to calibrate the HPGe detector, as well as three uranium sources of varying enrichment levels. Once the detector was calibrated, one uranium source was chosen as a standard. By determining each sample's ratio of ^{235}U to ^{238}U from the respective gamma spectrum, the enrichment of the other two uranium sources was approximated by comparing their ratios to that of the standard. This experiment gives students experience with HPGe gamma spectroscopy as well as uranium enrichment calculations.

The final experiment was the GM dead time determination lab. This lab had a GM detector and a ^{204}Tl beta split source. One half of the split source was used for statistics problems; a set of counts was taken and the mean, residuals, and standard deviation were calculated. The population was then compared to the standard deviation itself to see how many of the counts fell within it. The dead time of the detector was then experimentally determined. Each part of the split source was counted individually, and then the two were counted together. From these values, the dead time of the detector was then calculated.

With the three experiments completed remotely and the potential for the implementation of many more, this remotely accessible radiation detection laboratory shows considerable promise for full implementation in the future. The experiments were possible to complete from an off-campus computer as desired. That said, it is now clear that the system has its share of weaknesses as well. Internet connectivity issues can plague the connection quality; over long distances, insufficient bandwidth can cause slow operation and interruptions which are frustrating to the student. Worse still, a poor connection can cause the remote desktop application to kick out the user, which then requires a reconnection. Even in this case, however, all programs remain running while disconnected and can be resumed with little difficulty once reconnected.

Another flaw of the current system as it stands is that it is dependent on students "cleaning up after their work." If a student fails to properly shut down equipment including the webcam and the detectors, other students logging on may be unable to use those devices. As far as the computer is concerned, those resources are still claimed by the former account. A software solution may have to be implemented to correct this flaw.

As the experimental capabilities seem to be sufficient and can be freely expanded, future work in this area should also be directed at devising further experiments to implement on the system. A good candidate for a future experiment would be with Compton scattering; students would be tasked with analyzing how scattered gamma radiation changes with the angle at which it scatters, both in energy and relative intensity. Another possible experiment would involve neutron detection. This could involve comparing the capabilities of ^{3}He and BF_3 detectors, and observing how shifting polyethylene blocks in the detector arrangement can influence the detection of neutrons (e.g. imposing blocks between the source and the detector.) A significant challenge in the development of this technology would be the implementation of a mechanically challenging lab such as alpha detection. A lab involving multiple alpha sources would require working with vacuums and complex actions on the part of the lab controls in order to properly exchange sources in the detector. If this could be accomplished, however, there would be few remaining limitations on what nuclear radiation detection experiments could be accomplished by remote lab.

There is significant need for improvements on the connection method. Over long distances, the system as it stands suffers from a lack of visibility and sluggish response time. Despite the complications, however, the system does work. It is possible to physically carry out a properly set up experiment without being anywhere near the lab itself. With this serving as the groundwork for future fine-tuning and expansion, bringing online nuclear radiation lab courses to Texas A&M could quickly become a reality.

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APPENDIX A

Laboratory 1

Gamma Ray Spectroscopy Using NaI Scintillation Detectors

Purpose

The purpose of this laboratory is to study the use of NaI detectors for the measurement of gamma sources. The student will setup a NaI detector system using a Canberra MCA and spectrum analysis software, learn how to calibrate the system in energy, and identify an unknown source.

Materials Needed

The following will be provided by the instructor:

1. A set of industrial sources
2. Experiment station computer
3. NaI detector
4. an OSPREY digital MCA

The student should have the following:

1. an internet-capable computer
2. a calculator
3. your notebook
4. a copy of these procedures
5. a pen

Experimental Procedure

The table below will help in the energy and efficiency for this experiment.

Position	Source	Half life (yr)	Energy (keV)	Branching Ratio	Assay Date	Assay Activity
1	Cs-137	30.07	662	0.85	08/2010	1 µCi
2	Co-60	5.27	1173	1	08/2010	1 µCi
			1332	1		
3	Na-22	2.6	511	1.8	07/2016	1 µCi
			1275	1		
4	Ba-133	10.5	356	0.62	08/2010	1 µCi
			81	0.33		

Connecting to the Experiment Station

Your instructor will arrange for you a time to use the experiment station, an IP address to connect to, and login information for the experiment station. Record this information, as you will need it to connect to the experiment station.

Windows Instructions

1. Connect to the Texas A&M network. Help for this topic can be found at http://it.tamu.edu
2. On your computer, open up the Start menu and search for **Remote Desktop Connection** and open it.
3. Click on **Show Options**. Enter the IP address given by your instructor in the **Computer:** field.
4. Click **Connect**. When asked for login information, choose **Other** and enter **NE\username** for the user name (where “username” is your NE account name), and your NE account password as the password. Your NetID will not work.
5. You are now connected to the experiment station.

NaI System Setup and Energy Calibration

1. Open Canberra GENIE (search for Gamma Acquisition and Analysis), LabView 2015 **32-bit**, and the Logitech Webcam Software. Once in LabVIEW, click on “Open Existing” and navigate to and open the “Spectroscopy Stepper” program in “C:\LabVIEW Programs.”
2. In the Stepper window, press “Run.” See Fig. A1.

Fig. A1 – The Run button on the left end of the toolbar.

3. In GENIE 2000, open the detector MID file “OSP##” and set the HV to **800 V**. **(MCA>Adjust>HV).** Turn on the HV. Select the **Filter** button. Set rise time to 0.800 μs and flat top 0.2. Select the Gain button and adjust the LLD to 1.5%.
4. **Cs-137 Measurement.** Select the first source (Cs-137) and press **Start Move**. Wait for the source to rotate fully into position.
5. Set the limit of your spectrum to 2 MeV by using ratios. The channel limit on your spectrum is 2048. In a 2 MeV spectrum 2 MeV = 2048. At what channel should the 662 keV photopeak from Cs-137 fall on? Start acquiring a spectrum. Adjust the coarse and fine gains until the photopeak is approximately at the calculated channel.
6. Once the peak is near the specified channel, acquire a spectrum for 180 s (**MCA>Acquire Setup**).

7. Using the Canberra GENIE-2000 software, energy-calibrate the spectrum using the 662 keV photopeak. On the menu bar select **Calibrate – Energy Only Calibration.** The calibration window will open enter the energy and centroid channel number for the peak and click the **Accept** button. Record the channel and energy information used in the calibration.
8. Acquire the peak area(s) for the spectrum. First go to **Analyze> Analyze>Peak locate>VMS standard Peak Search.** Then go back to the **Analyze>Peak Area>Sum/Non-linear LSQ Fit…**. Record the net count rate and count uncertainties.
9. Identify the channel number and energies for the following spectral features: backscatter peak, Compton edge and photopeak.
10. **Co-60 Measurement.** Select the Co-60 source and press **Start Move**. Wait for the source to rotate fully into position.
11. Acquire a spectrum for 180 s.
12. Using the Canberra GENIE-2000 software, energy calibrate the detector system using the two photopeaks from Co-60. You can do this by going to **Calibrate>Energy Full>By Nuclide List**. Be sure to check the “append to existing calibration,” or the Cs-137 calibration **will be lost**. Select Co-60 from the list. Another window will appear listing the photopeaks. You can calibrate using 1 of two methods:
    a. You can click on the **Auto** button and the program should automatically set channel numbers for your peaks.
    b. OR you can manually put your cursor on the centroid of the lower energy peak. Highlight the 1173 peak entry in the calibration window. Click the “Cursor” button. This will enter the channel number of the peak. Repeat this for 1332 keV.
13. Record the channel and energy information.
14. Use the **Analyze** tools to determine the peak area, uncertainty and FWHM of each peak. Record this data.
15. Repeat sets 8 - 12 for Na-22 and Ba-133. For Ba-133 using the Nuclide list the software will ask you to delete peaks that are near each other. Select the peaks with the larger abundance.
16. Plot the energy as a function channel (that you recorded) data in your notebook. Compare to this to the plot produced by Genie 2000 under **Efficiency>Energy Show**.
17. Plot the FWHM as a function energy data in your notebook. Compare to this to the plot produced by Genie 2000 (click on the Shape button).
18. Is the channel to energy relationship linear? What does the relationship look like for FWHM and energy?
19. Move to the unknown source(s) in Position 5.
20. Acquire a spectrum for 180 s.
21. Based on this spectrum, determine what isotope the unknown source(s) is. Use the **Options>Interactive NID** tool to assist you. Make sure “Show confirming lines” is turned on, as this will cause it to show where other peaks from a given nuclide *should* be if it is actually in your sample. Clicking on a line moves your spectrum cursor there, while clicking in the spectrum will choose a nuclide & line if it is close enough to one.

Efficiency Calibration

1. Using the count rate data and the known source activities, calculate the efficiency of the detector system at each peak energy.
2. Make a plot of the Efficiency as a function of Energy for your notebook.

Potential Post-Laboratory Exercises

1. Plot energy as a function of channel number
2. Plot FWHM as a function of channel number
3. Plot Efficiency as a function of channel number
4. Write a full lab report explaining how the detector was energy calibrate and how this calibration was employed to identify an unknown source.

Laboratory 2

Uranium Enrichment Measurements with HPGe's

Purpose

The purpose of this laboratory is to gain operational experience with a HPGe detector. In this experiment, students will utilize a HPGe detector system and spectrum analysis software to identity and determine the activity of an unknown source. In addition, students will use the simple comparator method to calculate the enrichment of various uranium samples.

Materials Needed

The following will be provided by the instructor:

1. a natural uranium source
2. an enriched uranium source
3. a depleted uranium source
4. a HPGe detector
5. a high voltage power supply
6. Experiment station computer
7. a digital MCA system with spectrum analysis software

The student should have the following:

1. an internet-capable computer
2. a copy of these procedures
3. a pen
4. your notebook
5. a calculator

Position	Source	Half life (yr)	Energy (keV)	Branching Ratio
1	Cs-137	30.1	662	0.85
2	Eu-152	13.5	122	0.29
			245	0.076
			344	0.27
			779	0.13
			964	0.15
			1086	0.10
			1112	0.14
			1408	0.21

Table A1 – List of radionuclides used in this experiment.

Experimental Procedure

Connecting to the Experiment Station

Your instructor will arrange for you a time to use the experiment station, an IP address to connect to, and login information for the experiment station. Record this information, as you will need it to connect to the experiment station.

Windows Instructions

1. Connect to the Texas A&M network. Help for this topic can be found at http://it.tamu.edu
2. On your computer, open up the Start menu and search for **Remote Desktop Connection** and open it.
3. Click on **Show Options**. Enter the IP address given by your instructor in the **Computer:** field and X\username into the **User name:** field, where X is the IP address and username is the login name supplied to you.
4. Click **Connect**. It will shortly ask for a password, enter the one supplied by your instructor.
5. You are now connected to the experiment station. Check that Canberra GENIE, LabView, and the webcam software are all open. If not, follow the shortcuts on the desktop to open these programs. Open LabView using the "Spectroscopy Stepper" shortcut, then enable the VI by pressing the Run button in the upper left corner (Fig. A2). Enable the motor itself as well.

Fig. A2 – The Run button on the left end of the toolbar.

Create a library in GENIE

1. On the lab computer's desktop go to: **START>All Programs>GENIE 2000>Nuclide Library Editor.**
2. In the window that appears enter all possible source information. To accomplish this, first fill out the top most portion of the window which contains the name of the isotope you are adding. Hit **Add Nuclide**. You can leave uncertainty blank. Now fill out the energy line information and hit **Add Line**. You can leave the "uncertainty" at 0. Do this for each nuclide in Table A1.
3. Add additional sources. Go to **Options > Extract**. Open Stdlib.nlb. Click on Zn-65, Eu-152, Am-241 and Bi-214. Hit OK. Several peaks will show for each of these sources. Delete lines that are less than 5% abundant.
4. Now add U-235 and 238. Go to **Options > Extract.** Open ANSI_GammaGuru.nlb. Select U-235 and U-238+dau. Do not delete any peaks.
5. Save your library as distance605lib.

Energy Calibration

1. Turn on the GENIE software. Go to **File > Open**. Select the **Detector** button and choose the HPGe .mid file. Go to **MCA > Adjust**. Change the LLD to 0.5%. Verify that the HV potential and polarity are properly set. Turn on your HV. Set the acquisition time to 120 s. (**MCA > Acquire Set up…)**
2. Select the Cs-137 source and press **Start Move**. Set your MCA to a 3 MeV scale. Your maximum channel is 8192. Make sure you record the centroid for the Cs-137 photopeak and show how you got to it in your lab notebook.
3. Once your scale is set, acquire a spectrum for 120 s.
4. Once 120 s has elapsed calibrate the spectrum. **Calibrate > Energy Only.** Put your cursor on the peak centroid**.** Click the **Cursor** button, then enter the peak energy. Hit **Accept**. Record the channel number of the photopeak, backscatter peak and Compton edge.
5. Use the "Analyze>Peak Locate>Unidentified 2nd Differential…" command to perform a peak search. Remember to check the "Generate Report" box in order to tell GENIE to print the report to the window. Acquire the peak area for the spectrum using the "**Analyze>Peak Area>Sum/Non-linear LSQ Fit…".** Record the net count rate and count uncertainties for the peak.
6. **Eu-152 Measurement.** Switch to the Eu-152 source. **Count the Eu-152** source for 180 s.

7. Using the Canberra GENIE-2000 software, add the Eu-152 photopeaks to the energy calibration for the detector system. You can do this by using the **Energy Full > By Nuclide List** command. Select your 605lib. Remember to check "Append to Existing Calibration" so that it adds this calibration point to the existing calibration. Put the cursor on the spectrum over the peak centroid. Click on the **Cursor** button. Record the channel and energy information. Delete any peaks that do not have any relevance in your calibration.
8. Use the "**Analyze>Peak Locate>Unidentified 2nd Differential…**" command to perform a peak search. Remember to check the "Generate Report" box in order to tell GENIE to print the report to the window. Acquire the peak areas for the Eu-152 peaks listed in Table 1 using the "**Analyze>Peak Area>Sum/Non-linear LSQ Fit…".**

Efficiency Calibration

1. Go to **Calibrate>Efficiency>By Nuclide list.** Select Eu-152. Do **NOT** check "Append to existing calibration."
2. Click on the **Additional Information** button.
3. Enter the assay date on the source. For time enter 12:00:00.
4. Enter the activity of the source and add an uncertainty of 10%. Click the **Change** button and the information should update in the window.
5. Hit **OK** then hit **OK** in the remaining window. The efficiency calibration window should appear. Hit **Auto** on the bottom right of the window. Your peak efficiencies should automatically fill in. If they don't, you may not have recorded the spectrum for long enough or your energy calibration is off.
6. Once all of the efficiencies are entered hit **OK.**
7. Go to **Calibrate>Efficiency Show.** Record your efficiency curve.

Identification of an unknown source.

1. Switch to the unknown source. Take a 300 s spectrum.
2. Go to **Analysis>Executive sequence>NID Analysis with Report.**
3. Record the peak energies of what was found, determine what nuclide is present and its activity.

U Measurements

1. Switch to the first uranium sample, natural uranium. This sample will serve as your standard.
2. Acquire a spectrum for 10 minutes. This measurement time must be long enough that the 1001 keV peak for U-238 has a sufficient number of counts.

3. Go to **Analysis>Executive sequence>NID Analysis with Report.**
4. Using the GENIE-2000 analysis software, identify the peaks in the spectrum. Use the **Analyze>Peak Locate>Unidentified 2nd Differential…** command to perform the peak search. Remember to check the “Generate Report” box in order to tell GENIE to print the report to the window.
5. Record the peak energies of what was found, what the nuclides identified were along with the calculated activity. Record the net area of the 186 keV and 1001 keV peaks using the ROIs from the peak locate. **Keep these ROIs for the other uranium samples. Do not clear them.**
6. What activity for U-235 and U-238 did the software calculate?
7. Repeat steps 2-8 for a second uranium sample. Skip peak locate.
8. Using the simple comparator method discussed in class, estimate the enrichment of the second uranium sample.
9. Repeat steps 2-8 for a third uranium sample. Skip peak locate.
10. Using the simple comparator method discussed in class, estimate the enrichment of the third uranium sample.

Potential Post-Laboratory Exercises

1. Plot energy as a function of channel number
2. Plot FWHM as a function of channel number
3. Plot Efficiency as a function of channel number
4. Create a table listing the energy of each of the Cs-137 spectrum: photopeak energy, Compton Edge and backscatter peak. Compare the experimental energies to calculated energies from the Compton scattering formula.
5. Create a data table for each efficiency measurement.
6. Create a table showing the unknown source data and its identity.
7. Create a table with uranium
8. Write a full lab report explaining how the detector was energy calibrate and how this calibration was employed to identify an unknown source.

Laboratory 3

Gas-Filled Detectors, Counting Statistics, and Dead Time

Purpose

The purpose in this lab is to introduce the student to gas-filled detectors and to learn how to interpret data from these detectors. The student will specifically learn about the Geiger-Mueller counter. The student will study the signal produced from this detector using an oscilloscope. The student will also study the statistics involved in radiation detection using the detector. The student will then learn how to characterize the detector efficiency and the detector dead time. These values will then be used to determine the activity of an unknown source using counts from the detector.

Materials Needed

The instructor will provide the following:

1. A Geiger-Mueller counter
2. Lynx MCA
3. Experiment station computer
4. Tl-204 split source
5. Other radioactive source

The student should have the following:

1. an internet-capable computer
2. a copy of these procedures
3. their notebook
4. a pencil
5. a calculator

The Student should know the following:

1. Dead-time formula
2. How to calculate activity
3. Basic error propagation formula

Experimental Procedure

Connecting to the Experiment Station

Your instructor will arrange for you a time to use the experiment station, an IP address to connect to, and login information for the experiment station. Record this information, as you will need it to connect to the experiment station.

Windows Instructions

1. Connect to the Texas A&M network. Help for this topic can be found at http://it.tamu.edu
2. On your computer, open up the Start menu and search for **Remote Desktop Connection** and open it.
3. Click on **Show Options**. Enter the IP address given by your instructor in the **Computer:** field and X\username into the **User name:** field, where X is the IP address and username is the login name supplied to you.
4. Click **Connect**. It will shortly ask for a password, enter the one supplied by your instructor.
5. You are now connected to the experiment station. Check that Canberra GENIE, LabView, and the webcam software are all open. If not, follow the shortcuts on the desktop to open these programs. Open LabView using the "GM Rotate" shortcut as well as the "GM Linear" shortcut, then enable the VIs by pressing the Run button in the upper left corner. Enable the motors as well.

GM operating range

1. With the Genie gamma acquisition software, open the detector MID file "OSPREY##" and set the HV to **500 V**. **(MCA>Adjust>HV).**
2. Make sure the detector is in "Position A" (in the Linear VI) and that the movable half of the split source is placed next to the stationary half ("Position 2" in the Rotation VI).
3. Determine the operating voltage
   a. Set the software to record for 18 seconds (0.3 minutes).
   b. Starting at ~500 V increase your voltage 25 V until you register betas.
   c. Record the counts after every increase until you have left the GM region (This will occur when there is a sharp increase of counts). **DO NOT EXCEED 1000 V**
4. Pick an operating voltage about half way into the plateau.
5. If you see a decrease in the count, please provide the explanation.

Counting Statistics

1. Move the detector to Position A if it is not already. Take a 120 s background count, ensuring that the movable source half is not in front of it. Record the count.
2. Move the source to Position 1.
3. Take 40 sequential 6-second counts of the movable source and record these raw counts N.
4. Calculate the mean of these 40 counts N_{avg}. Tabulate $N\text{-}N_{avg}$.
   Note: The number ($N\text{-}N_{avg}$) is called the residual and can be positive or negative. If you add up all of the ($N\text{-}N_{avg}$) values in the table, the answer should be zero. If it is not, a mistake has been made. Calculate the standard deviation (σ) which is the square root of the mean. Sixty-eight percent of the observed data should lay within the range $N_{avg}+\sigma$ to $N_{avg}-\sigma$.

Detector Dead Time Measurements

1. The source used so far is part of a split source set. This source is designed such that each half of the source can be counted separately without too many losses, but when both parts are counted at the same time, substantial losses occur.
2. Count the movable half of the source at "Position A" for 30 seconds. Calculate the count rate and call this M_1. Record the count time, counts, and count rate.
3. Move the detector to "Position B," where the other half of the split source is positioned. Count the second half of the source for 30 seconds (or the same time length used in step 2). Calculate the count rate and call this M_2. Record the count time, counts, and count rate.
4. Now count both halves of the source at the same time for 30 seconds. With the detector still at Position B, move the second half of the split source to Position 2. This should place the sources together in front of the detector. Calculate the count rate and call this M_{12}. Record the count time, counts, and count rate.
5. Move the detector back to Position A and count background for the same count time used above. Calculate the background count rate and call this M_b. Record the count time, counts, and count rate.
6. From these values calculate the dead time.

Potential Laboratory exercises

1. Create tables of all the data
2. Calculate the mean of these 40 counts N_{avg}.
3. Calculate $N\text{-}N_{avg}$ in the table. Note, the number ($N\text{-}N_{avg}$) is called the residual and can be positive or negative.

4. Calculate the standard deviation (σ) which is the square root of the mean. Sixty-eight percent of the observed data should lay within the range $N_{avg}+\sigma$ to $N_{avg}-\sigma$. Is this the case?

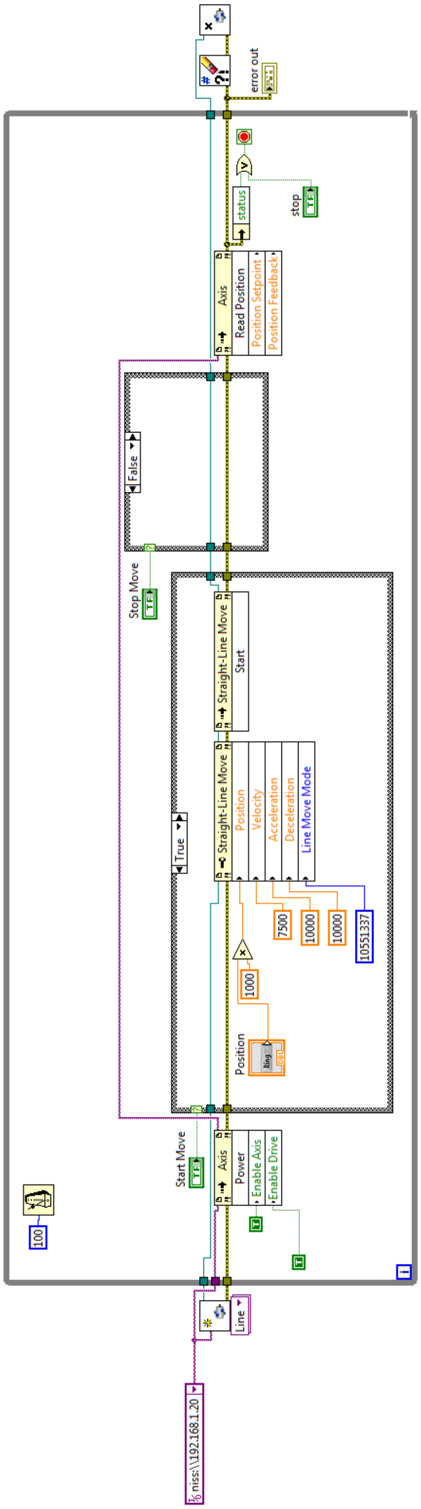
Calculate $(N-N_{avg})/\sigma$ and tabulate them. Round off the value for each entry of $(N-N_{avg})/\sigma$ to the nearest 0.5. For example, if $(N-N_{avg})/\sigma = +1.11$, then the rounded off value would be +1.0. Produce a histogram of the rounded off events and discuss. Hint: what should this histogram look like?

5. What is the dead time? What is the uncertainty in the value? How does this dead time compare to the accepted dead time (cite where you got the accepted dead time)?

6. Write a full laboratory report on the results of this lab.

APPENDIX B

Block Diagram for the Linear Slide VI



Block Diagram for Rotary Table VI