



PREPARATORY PROBLEMS

for the
First International Nuclear Science Olympiad
(1st INSO)

EXPERIMENTAL

1st INSO Preparatory Problems

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CONTENT

CONTENT.....	i
Q1. Locating an Orphan Source (10 pts)	1
Q2. Gamma Spectrometry (10 pts)	3
Q3. Half-life Experiment (10 pts)	8
Q4. Half-life Experiment - Computational.....	13
Q5. Gamma Shielding - Computational	18
Q6. Radiation Damage - Computational.....	24
QUESTION-SYLLABUS MATRIX.....	32
ACKNOWLEDGEMENTS	33
QUESTION FEEDBACK	34

Q1. Locating an Orphan Source (10 pts)

Experiment Guide

A. Experiment background/theory

An orphan source is a radioactive source that is sufficiently dangerous to require regulatory control. Orphan sources express a wide range of risks, such as radiation exposure, contamination, accidental exposure, radioactive material spread, risks for first responders, impact on the environment, long-term environmental consequences, and security issues. To reduce the possible effects of uncontrolled radioactive materials, it is crucial to give priority to prevention, early detection, and appropriate management of the orphan source.

B. Equipment List

Large room/area, sealed source with known activities, survey meters, a scale

C. Safety

To protect experimenters and the environment, keep in mind that handling orphan sources should only be done by people who have had the necessary training. If you are required to manage such a source, consider the following precautions: keep your distance, avoid direct contact, and wear personal protection equipment. Ensure that the radiation monitoring equipment is calibrated and working correctly and use radiation monitoring devices to continuously measure and monitor radiation levels.

Experiment Procedure

Students are provided with a radio-controlled car with survey meters and a sealed source with known activities. The task is to measure the count rates at a number of locations in a given room. With the obtained information, the participant will identify the location of an orphan radioactive source hidden under the surface of the room and its activity.

1	Calibrate the survey meters to obtain their efficiency ε .
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Q1-2
EXPERIMENT

2	Define the maximum uncertainty of the measurement.
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1.0 pt

3 Choose 3 locations for measuring the counts. Recording the counts and the amounts of time for measurement needed for the desired uncertainty. Calculate the CPS (counts per second) and its uncertainty for each location. 2.0 pts

4 What is the relation for CPS (c) for each location (x, y) ? 2.0 pts

5 Write final equations needed to find (x_0, y_0) . 3.0 pts

Q2. Gamma Spectrometry (10 pts)

Experiment Guide

A. Experiment background/ theory

Gamma-ray spectrometry is a science of quantification of radionuclides present in a material by the analysis of gamma-ray spectrum produced in a gamma-ray spectrometer. It is a very powerful non-destructive analytical technique used to identify and quantify radioactivity of gamma emitting substances. This technique has many applications as they are used in monitoring radioactivity in the environment.

B. Equipment List

Cs-137 and Co-60 check sources, NaI(Tl) detector with a multi-channel analyzer (MCA) detection and measurement system

C. Safety

Ensure that the check sources are handled safely by applying the time, distance, shielding (TDS) principle.

Experiment Procedure

A gamma-ray spectrometer consists of a gamma-ray detector and an electronics system to measure the gamma-rays incident to the detector (see Figure 1). In this exercise, you are to perform gamma spectrometry by quantifying the radioactivity of a given sample and setting up the counting system for measurement, with details to be discussed in the next sections.

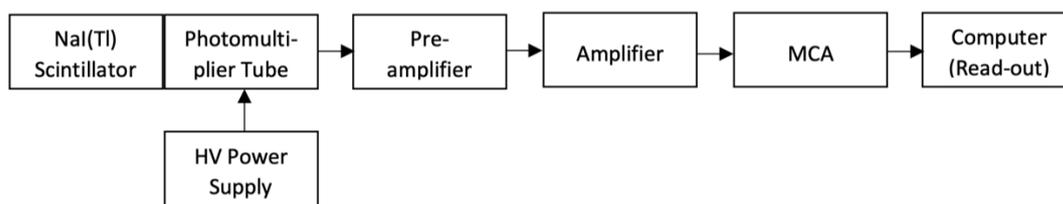


Figure 1. Diagram for Gamma-Ray Spectroscopy MCA Detection System with NaI(Tl) Detector

Part 1. Energy calibration (1.5 pts)

Perform gamma spectrometry with the Co-60 and Cs-137 check sources. Obtain the spectrum files from the software you used for the procedure.

1.1 Plot the counts/intensity as a function of channel in MS Excel. Identify the photopeak centers (channel) and fill-out Table 1 with the corresponding channel numbers. Use the photopeak to identify the radionuclide (for example, if the photopeak energy is 662, then the radioisotope is Cs-137) 0.5 pts

1.2 After the radioisotopes have been identified, perform the calibration by finding the relationship between the MCA channels and photopeak energy. 1.0 pt

Table 1. Energy Calibration

Event	Energy (keV)	Peak Channel Number
Cs-137 photopeak	661.6	
Co-60 photopeak (1)	1173.2	
Co-60 photopeak (2)	1332.5	

Table 2. Spectrum Artefacts

Artefact / Event	Energy (keV)	Peak Channel Number
Compton Edge of Co-60		
Compton Edge of Cs-137		
Backscatter of Co-60		
Backscatter of Cs-137		
Sum peak of Co-60		

Part 2. Identify spectrum artefacts (1 pt)

The **photopeak** refers to the region of the spectrum caused by the complete photoelectric absorption of gamma-rays by the detector. Peaks at the lower energies of the photopeak are coming from the **Compton scattering** interaction, two **escape peaks** at energies of 511 and 1022 keV are due to pair production when one or both annihilation photons escape and a **backscatter peak** when gamma-rays hits a material around the detector and scattered back into the detector. Higher energy peaks can also be measured

when two or more gamma-rays strike the detector almost simultaneously, appearing as **sum peaks** with energies up to the value of two or more photopeaks added or coincidence sum when two decay events occur within the resolving time of the detector.

2.1 Complete Table 2 by calculating the energy of the Compton edges, backscatter peak and sum peaks. Identify the spectrum artefacts and corresponding peak channel. Refer to the decay scheme for further information regarding the decay events. 1.0 pt

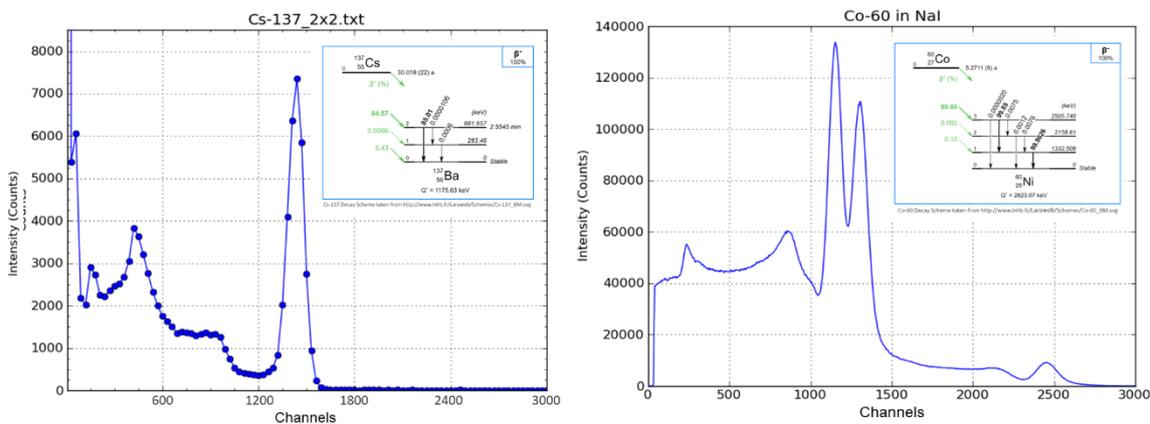


Figure 1. Sample gamma spectra for Cs-137 and Co-60. Decay schemes in inset photo.

Part 3. Obtain efficiency curve (4.5 pts)

In gamma spectrometry, we relate the photopeak area in our spectrum to the amount of radioactivity. For this, we need to perform **full (or photopeak) energy peak efficiency**. The **Full-Energy Peak Efficiency Calibration** is the ratio of the number of photopeak **intensity** or counts detected by the detector to the number of gamma-rays emitted by the source (activity × gamma emission probability) and depends upon the geometry of the source and the detector. Efficiency is in units of **counts/disintegration** and is obtained using Equation 1.

$$\text{Efficiency} = \text{Activity} / (\text{Counts} \times \text{emission probability}) \quad (\text{Equation 2})$$

The probability of gamma-ray interaction varies with the gamma-ray energy and target material. Efficiency is strongly dependent on energy, thus, the need to calibrate for a wide range of energies covering the energies of the nuclides of interest. The source geometry, sample matrix for self-absorption effects and pulse pile-up are the factors affecting the efficiency.

3.1 From the raw spectrum text file, obtain the counting time and date of irradiation. 0.5 pts

3.2 From the spectrum in Part 2, estimate the total counts under the corresponding photopeak area of each radionuclide. 1.0 pt

3.3 Relate the photopeak area to the corrected activity and compute for the corresponding efficiency using Equation 1. Refer to the Standard Certificate of the calibration source used in Table 2. 2.0 pts

3.4 Plot the efficiency calibration curve as a function of energy. 1.0 pt

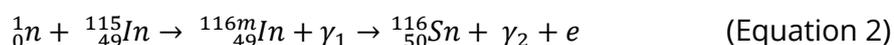
Table 3. Source Description for Efficiency Calibration

Radionuclide	Energy (keV)	Half-life, T1/2 (year)	Emission Probability (%)	Activity (mCi)	Reference Date
Cs-137	661.6	30.08	85.1%	0.010 ± 0.0002	27-Apr-1999
Co-60	1173.2	5.27	99.85%	0.050 ± 0.0002	11-Jan-2019
	1332.5		99.98%		

Part 4. Quantify the amount of radioactivity in the activated Indium foil (3 pts)

After performing all the calibration requirements for a gamma-ray spectrometer – energy and full-energy efficiency, you are now equipped to perform quantitative analysis and estimate the activity (and concentration) of radionuclides in your sample.

Indium-115 irradiation foil has been widely used as a passive detector for neutron flux measurement in a mixed neutron and gamma field due to its insensitivity to photons. Indium has two naturally occurring isotopes – In-115 (95.719%) and In-113 (4.281%). In-115 emits radiation when exposed to a neutron field. It has a half-life that is convenient for irradiation and radiation counting. It emits beta-particles and gamma-rays, which is given in the Equation 2.



In-116m decays by 100% beta emission and emits gamma-rays with the energies and emission probability listed in Table 3. The beta-particles and gamma-rays can be quantified to estimate the radioactivity. The discussion here is limited to the gamma spectrometry of the irradiated foils.

Radionuclide	Energy (keV)	Half-life, $T_{1/2}$	Emission Probability (%)
In-116m	162.39	2.18 sec	37.2
	416.90		85.1
	1097.28	54.29 min	99.85
	1293.56		99.98

Obtain spectrum of sample until all photopeaks are clearly distinguishable (>100,000 counts peak area). Save spectrum as a text file. See sample spectrum here - [Sample Spectrum.txt](#)

4.1	Estimate the photopeak area corresponding to the In-116m gamma ray energy to obtain the counts.	1.0 pt
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4.2	Estimate the efficiency for the corresponding photopeak from the interpolated value for the energy in the efficiency curve in Part 3.4.	0.5 pts
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4.3	Calculate the induced radioactivity. Refer to the information given in Table 3.	1.5 pts
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Q3. Half-life Experiment (10 pts)

Experiment Guide

A. Experiment background/ theory

The rate of decay of radioactive atoms at time t is given by the following relation.

$$-\frac{dN}{dt} \propto N(t)$$

As $dN/dt = (N_2 - N_1)/(t_2 - t_1)$ is negative due to decrease in number with time, whereas, on right side both λ and N are positive. To balance as equation, a negative sign is always marked.

$$-\frac{dN}{dt} = \lambda N(t)$$

In above equation, λ is decay constant which is decay rate per atom. Solving differential equation (Separation of variables)

$$\int \frac{dN}{N} = - \int \lambda dt$$

$$\ln(N) = -\lambda t + C$$

$$N(t) = e^{-\lambda t + C} = e^{-\lambda t} \times e^C$$

Where C is constant of integration which can be determined by using initial condition i.e; $N(0) = 0$.

$$N(0) = e^{-\lambda \times 0 + C} = e^C$$

Thus, $e^C = N(0)$ is the initial number of radioactive atoms.

$$N(t) = N(0)e^{-\lambda t} \tag{1}$$

Physically, $N(0)$ is the initial number of radioactive atoms. The graph shows that the exponential starts decaying from this value.

The time required to decay half of the radioactive atoms is called its half-life which is used to determine decay constant. Putting $N(t) = N(0)/2$, $t = T_{1/2}$ in equation (1).

$$N(0)/2 = N(0)e^{-\lambda T_{1/2}}$$

$$\frac{1}{2} = \frac{1}{e^{\lambda T_{1/2}}} \Rightarrow e^{\lambda T_{1/2}} = 2$$

Taking \ln on both sides.

$$\lambda T_{1/2} = \ln 2$$

$$\lambda = 0.693/T_{1/2}$$

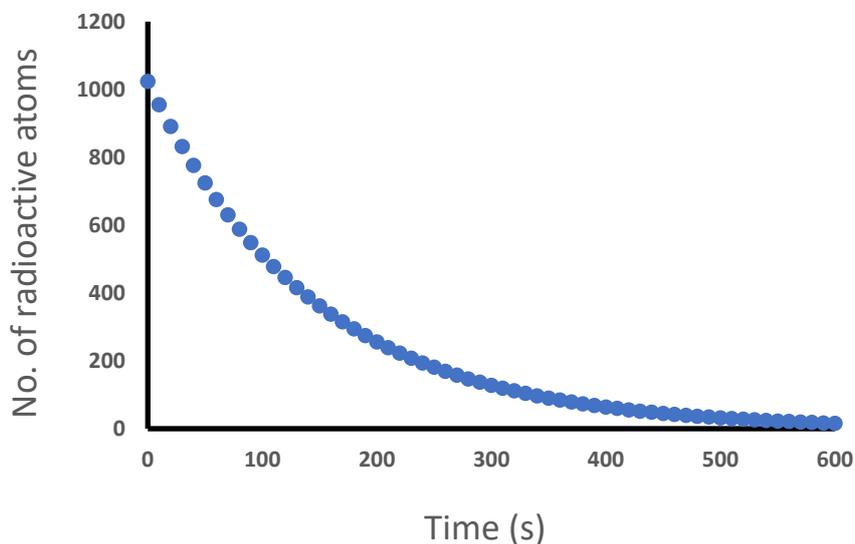


Figure 1. Variation of the number of radioisotopes versus time

The decay of radioactive atom results in the emission of radiation (e.g; alpha, beta, and gamma). The radiation, for instance gamma, is detected by a radiation detector and appears as a count on the counter. While counting the emitted radiation, the term activity is used.

$$A(t) = \lambda N(t)$$

$$\ln[r(t)] = \ln[r(0)e^{-\lambda t}] = \ln[r(0)] - \lambda t$$

Clearly, putting $y = \ln[r(t)]$, $m = -\lambda$ and $\ln[r(0)] = c$, one obtains

$$y = mt + c$$

By plotting a graph between y and t , a straight line with slope equal to $-\lambda$ and y -intercept of $\ln[r(0)]$ is obtained. Both parameters can be extracted from the graph.

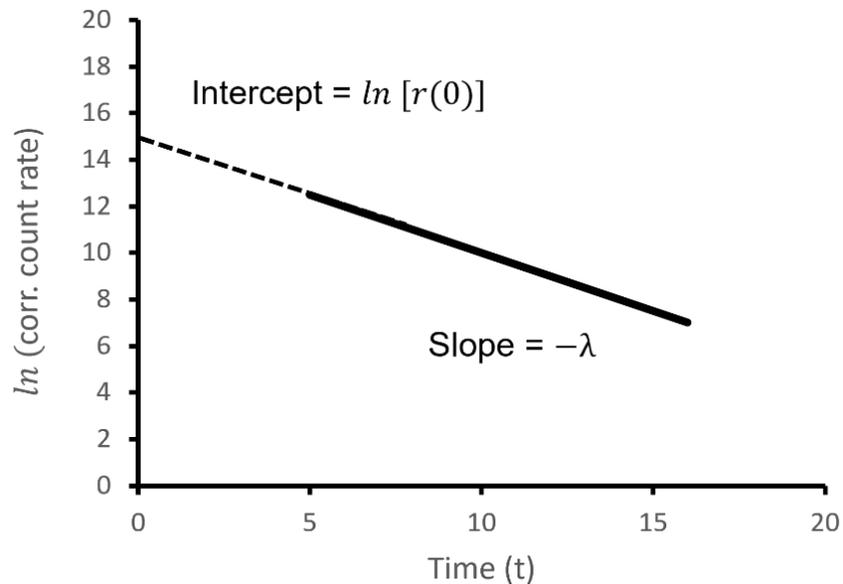


Figure 2. Natural logarithm of corrected count rate versus time.

B. Equipment List

GM detector, Inverter, Stand, Cables, Radioisotopes (In-115m, Ag-108, Ag-110), Lead shielding, Counter and timer

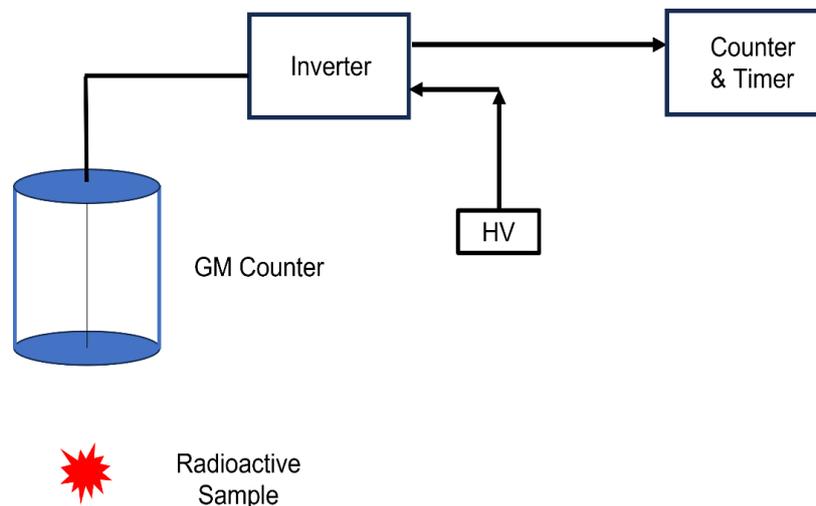


Figure 3: Experimental Setup

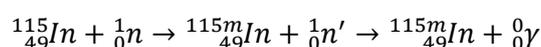
C. Safety

Ensure that the radioactive material is handled safely by applying the time, distance, shielding (TDS) principle.

Experiment Procedure

Short-lived single radioisotope

The half-life of a short-lived isotope can be measured experimentally by using a simple radiation counter. Naturally occurring radioisotopes are very long lived. Short-lived isotopes are artificially prepared by bombarding stable atoms with neutrons as shown below.



The half-life of the radioisotope ${}_{49}^{115m}\text{In}$ is 4.5 hr. As the radioactive atoms decay in the sample, a radiation quantum is emitted. A detector, for instance GM, counts the radiation quanta for a set interval of time T . Then, the count rate r represents decay rate. The count rate when plotted with time gives the half-life.

The following steps are needed:

- Prepare a plot similar to what is shown in Figure 1.
- Select the time interval for counting. The time interval should be as small as possible e.g. 10 s.
- Select the mode on the counter such that dwell time is minimum. Note that the counter will display counts for dwell time and then, start next reading. (Note: In case of missing a reading leave the space in the observation table)
- Take background measurements. Table 1 can be used to record the experiment data.
- Place the sample at a suitable distance from the GM detector and note the time as zero in Table 1, and simultaneously start measurement.
- Note the counts after regular intervals of time and calculate the count rate.
- Subtract the background count rate to obtain corrected count rate.
- Plot a graph between count rate versus time.
- The time interval in which the count rate falls to one half is the half-life of the radioisotope.

Table 1: Observation data

Background counts (N_{bkg}): _____				
Measurement Time Interval (T): _____				
Background count rate ($r_{bkg} = N_{bkg}/T$): _____				
Time (t)	Counts (N)	Count rate ($r = N/T$)	Corrected count rate $r_{cor.} = r - r_{bkg}$	ln ($r_{cor.}$)

1.1 Record the background count rate. 0.5 pts

1.2 Record the observations and make calculations according to Table 1. 1.5 pts

1.3 Plot the graph between count rate and time and find half-life from this graph. 2.0 pts

1.4 Plot the graph between natural logarithm of count rate and time. 1.5 pts

1.5 Use the least square method to fit straight line to the semi-log plot. 2.0 pts

1.6 Determine the half life from the slope of the fitted line. 1.5 pts

1.7 Comparison of two measured half-lives and comments on the results. 1.0 pts

Q4. Half-life Experiment - Computational (10 pts)

Experiment Guide

A. Experiment background/ theory

Please refer to Section A of Q3.

B. Software Description

Octave is an open-source numerical computing software that provides a high-level programming language, primarily designed for numerical and linear algebra tasks. It's similar to MATLAB and is widely used in academia and industry for scientific and engineering computations. Octave supports matrix operations, plotting, data analysis, and the implementation of algorithms, making it a versatile tool for various applications. It's particularly popular for its ease of use in mathematical modeling, simulation, and prototyping.

- You can download octave software from the link (<https://octave.org/download>).
- Alternatively, you may follow the link: https://drive.google.com/drive/folders/17aYNSa98qGOkqtNIGYu_LktnE_hiCekk?usp=drive_link to download the code, or scan the QR-code below:



- You can learn more about Octave from online sources. The QR-code below provides the link to a useful tutorial.



INSO Notes

- In the actual competition, if a similar experiment problem is selected, the full code will be provided to the students with detailed instructions. Students are typically not instructed to write a full code but may be asked to write some parameters in the code.

C. Software Guide

Picture below shows the front page of the software, where the user can write/modify the code in the editor, save changes, run the simulations and copy the experiment results.

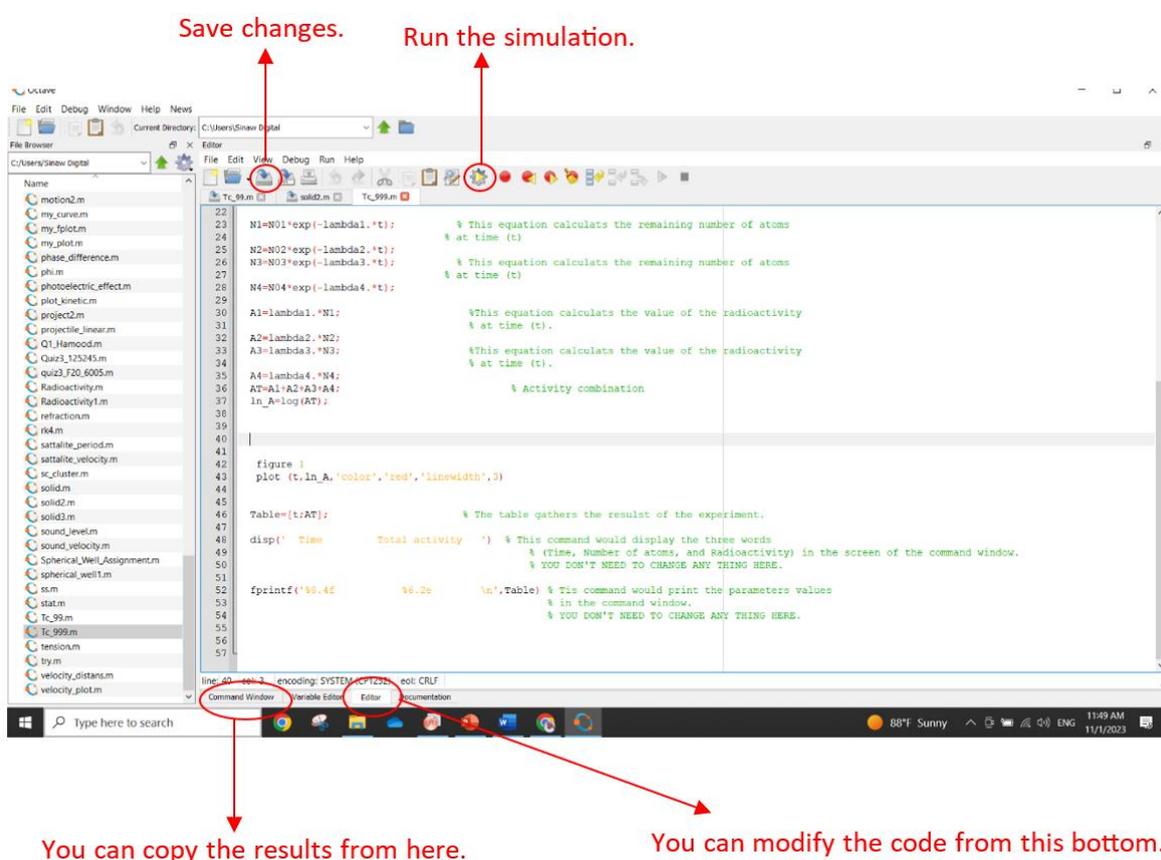


Figure 1: User Interface of the Octave Code

Experiment Procedure

Part 1. Calculation of activity (5 pts)

You are given an Octave code so that you can adjust the parameters according to the given instructions. The code represents a decay experiment of the technetium-99m (${}_{43}^{99}\text{Tc}$)

radioactive material. Refer to the picture given in the appendix (1) to have a clear understanding about the content of the code, main bottoms to adjust the parameters, and how to run it.

- Refer to Figure 1 to have a clear understanding about the content of the code, main bottoms to adjust the parameters, and how to run it.
- If you run the code immediately without any changes it will show you the graph (N_t) of number of remaining atoms versus the time in (hours).
- The half-life of (${}^{99}_{43}\text{Tc}$) is 6hrs, adjust the value of $T_{1/2}$ in the code (line 3) to be in minutes.
- The molar mass of the (${}^{99}_{43}\text{Tc}$) is (98.9 g/mol). Referring to the initial mass of the (${}^{99}_{43}\text{Tc}$) given in the code, use the Avogadro number ($6.02 \times 10^{23} \text{ mol}^{-1}$) to calculate the number of (${}^{99}_{43}\text{Tc}$) atoms at ($t=0$). Put your answer in the line 5 of the code (For example if $N_0 = 5 \times 10^{30}$ write it as 5e30).
- Adjust the time in line 9 of the code to be in minutes with the time interval of 5 min.
- Now save the changes and run the code. Then click on the command window and copy the values of Time (t), Number of atoms (N), and Activity (A). Now use these values to plot two graphs (N_t) and (A_t) in an excel sheet.

1.1 Write down the steps for the calculation of (N_0). 1.0 pts

1.2 Copy the graphs of (N_t) and (A_t) obtained in step **f** and paste them here. 2.0 pts

1.3 Using the obtained values from the code, fill the Table 1 with the values of radioactivity and the number of atoms at three different times ($t = 0.5$ hrs), ($t = 1.5$ hrs), and ($t = 3$ hrs) 1.0 pts

Table 1. Change in activity and number of atoms with time

	0.5 hrs	1.5 hrs	3 hrs
Activity, A (Bq)			
Number of atoms, N			

- 1.4** Estimate the radioactivity (in Ci) of the ($^{99}_{43}\text{Tc}$) after 20 hrs from the decay beginning. At this time, by what percent the radioactivity reduced compared to the decay beginning? 1.0 pts

Part 2. Activity of a mixture (5 pts)

Consider this scenario: It is your first day working in a radioactivity analysis laboratory. Your supervisor asks you to perform analysis on a mixed sample of radioactive elements. The results of activity measurements of the mixture are given in Table 2.

Table 2. Activity measured at different times.

Time (h)	Activity (Decays/s)
0	7500
0.5	4120
1	2570
1.5	1790
2	1350
2.5	1070
3	872
4	596
5	414
6	288
7	201
8	140
9	98
10	68
12	33

- 2.1** State a method to calculate how many different nuclides are present in the mixture? (show your math calculations, plots, fittings) 2.0 pts

- 2.2** According to your answer to part (2.1), determine the half-life of each nuclide in the mixture? 1.0 pt

2.3 Referring to your answer in part (1), determine How many nuclei of each type are initially present in the sample. 1.0 pt

2.4 How many nuclei of each type are present at $t = 5.0$ h? Give your comment. 1.0 pt

Q5. Gamma Shielding - Computational (10 pts)

Experiment Guide

A. Experiment background/ theory

The Philippine Nuclear Research Institute (PNRI) has a multifaceted facility, currently partitioned by lead-based glasses. One of these facilities stores a gamma radiation source, which emits monoenergetic photons with an energy of 1.173 MeV. During experiments, this gamma source is removed from its storage box, inadvertently exposing workers in adjacent facilities to gamma radiation. The lead-based glasses serve as a crucial line of defense, acting as a radiation shield to reduce the transmitted radiation to levels deemed acceptable. However, exposure to lead can have detrimental effects on various body systems and poses a particular risk to women of child-bearing age. In light of these potential health risks and in an effort to promote safety, the PNRI is contemplating replacing these glasses with a material that is less harmful. Several glasses shown in Table 1 are currently under consideration as potential replacements for the existing lead-based glasses.

Table 1. Compositions of potential replacements glasses.

Glass	Elemental composition (wt%)
A	Li(7.2); B(2.24); O(50.15); P(25.7); Te(14.71)
B	Li(3.75); B(1.17); O(35.73); P(13.39); Te(45.96)
C	B(1.48); O(19.97); Na(1.43); Al(2.16); Si(5.34); K(1.12); Ba(52.51); Bi(15.99)
D	B(0.88); O(16.07); Na(0.86); Al(1.29); Si(3.19); K(0.67); Ba(40.27); Bi(36.77)
E	B(5.32); O(23.6); Mo(9.44); Bi(61.65)

One way to measure the material's efficacy in absorbing radiation is to investigate its mass attenuation coefficient, symbolized as μ/ρ . This coefficient serves as a crucial metric, quantifying the extent of radiation absorption per unit mass of a given shielding material. The formula for attenuation is given by:

$$I = I_0 e^{-\left(\frac{\mu}{\rho}\right)\rho x}$$

where: I is the final intensity, I_0 is the initial intensity, μ is the linear attenuation coefficient of the material, ρ is the density of the material, and x is the thickness of the material.

B. Software Description

EpiXS (available at <https://www.pnri.dost.gov.ph/index.php/downloads/software/epixs>) is a Windows-based application software developed by Frederick C. Hila and his team at PNRI. It's designed for photon attenuation, dosimetry, and shielding, and is built on the foundations of EPICS2017 from ENDF/B-VIII.0 and EPDL97 from ENDF/B-VI.8.

The software can perform data library interpolation in the energy range of 1 keV to 100 GeV. It can calculate various parameters such as:

1. Partial or total cross sections (σ)
2. Mass attenuation coefficients (μ/ρ)
3. Linear attenuation coefficients (μ)
4. Mean free paths (mfp)
5. Half-value layers (hvl)
6. Effective atomic numbers (Z_{eff})
7. Electron densities (N_{eff})

The software also boasts the ability to determine buildup factors for energy absorption (EABF) and exposure (EBF), in compliance with the ANSI/ANS-6.4.3-1991 standards established by the American Nuclear Society. It's versatile enough to handle computations for any material specified by the user. The software's foundation is the C# language, and it's built using the Windows Form App in Visual Studio 2019 (.NET Framework 4.7.2).

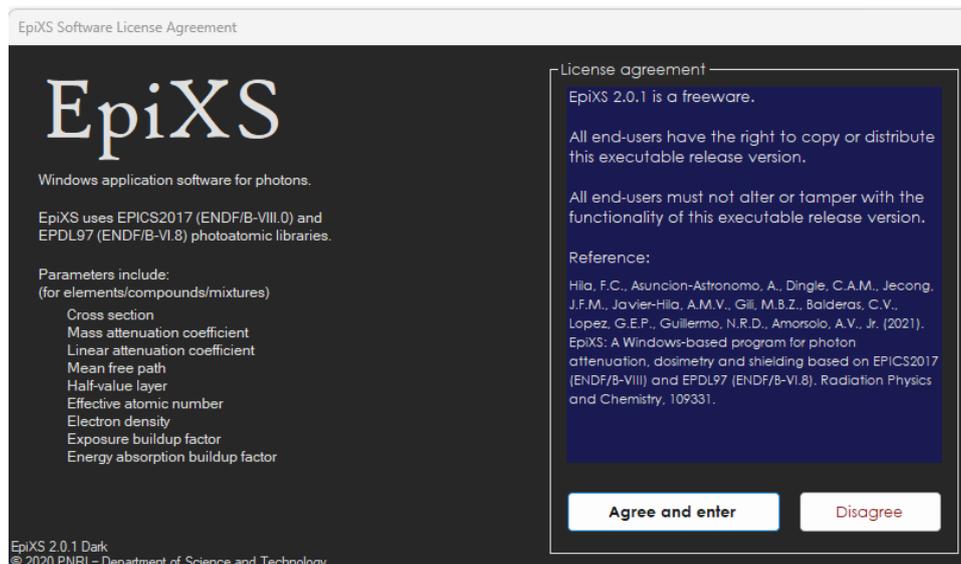
EpiXS is designed to be user-friendly and allows for quick interactive graphing and data tabulations

C. Software Guide

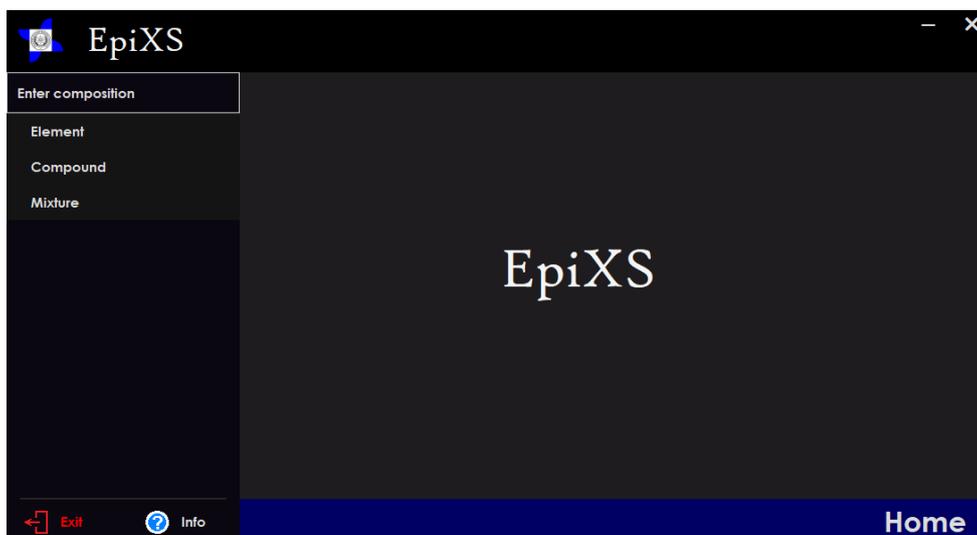
Initiating the EpiXS software is as simple as tapping on the icon displayed below:



The main menu interface is displayed below. By selecting "**Agree and enter**", access to the main simulator is granted.



Upon choosing “**Enter composition**” in the subsequent interface, a prompt will appear for the material type: **element, compound, or mixture**. This can be selected as illustrated below.

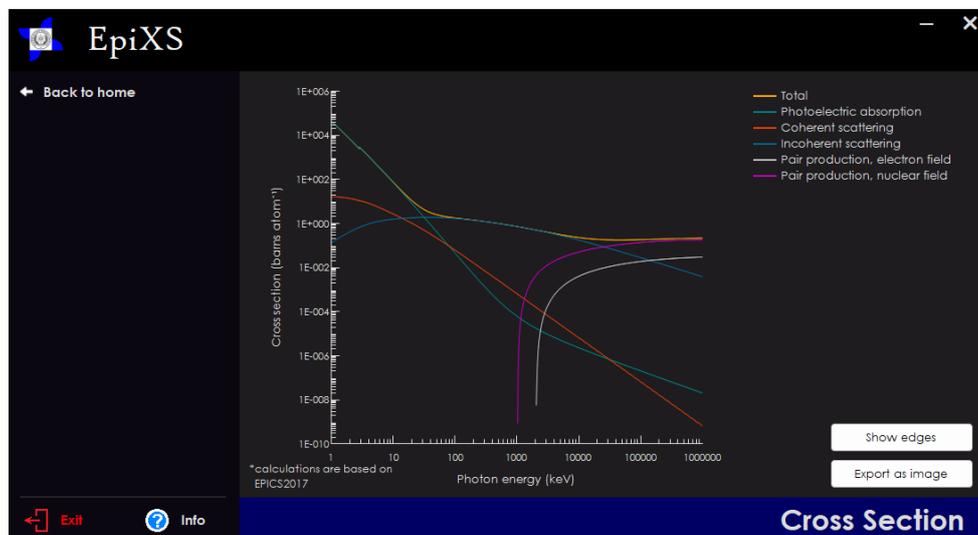


- **Elements** - Elements can be chosen either by their atomic number or their chemical symbol.
- **Compound** - For compounds, chemical formulas should be provided in standard chemical notation, adhering to the proper use of upper- and lower-case letters. Owing to the limitations of the software, subscripts are required to be written in line. As an example, the formula for dihydrogen monoxide, commonly known as water, should be entered as H₂O. Please note that the inclusion of parentheses, spaces, and dots is not supported by the software.

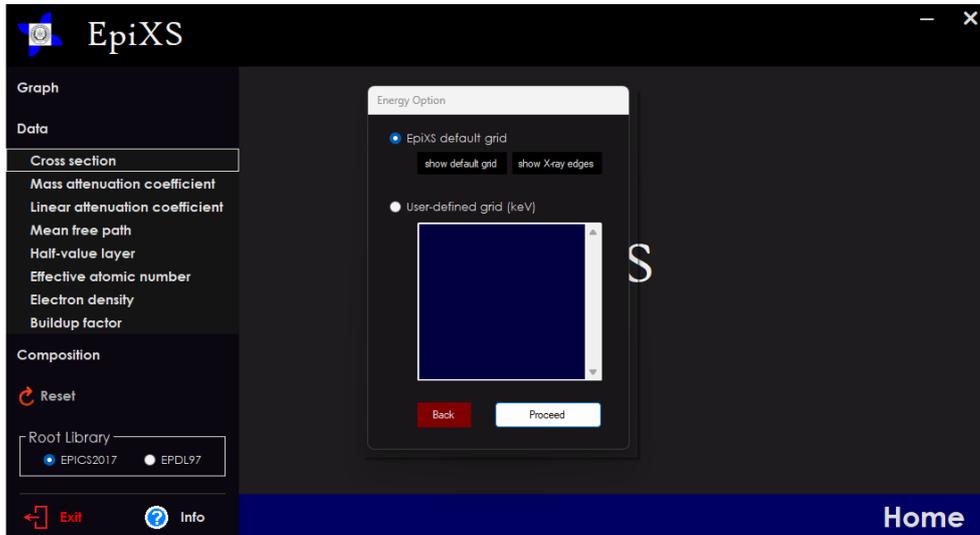
- Mixture** - Mixtures can be composed of either “elemental” or “compound” components, or both. Users are required to provide the chemical symbol or formula (as outlined above), along with the weight fraction for each component in the format: *<compound><space> <weight>*. The software utilizes this information to calculate the weight fractions of each atomic constituent and their total sum. If the sum of the weight fractions doesn’t equal one, the software will still accept the input data and adjust the weight fractions so their total equals one.

Once the material type is selected and all required information is entered in the appropriate format, the “**Proceed**” button can be clicked. It’s important to note that providing the material’s density is optional. However, without this parameter, calculations for the μ , mfp, and hvl cannot be performed.

In the next interface, the computed parameters can be viewed either as a graph or as data, based on preference. If the desire is to visualize any output parameter as a function of photon energy, the “**graph**” button should be selected as shown below.



Conversely, if the preference is to see any output parameter in a tabular format, the “**data**” button should be chosen as shown below.



With the “**data**” option, there is the flexibility to:

- 1) Restrict output to the standard energy grid,
- 2) Incorporate additional energies into the standard grid, or
- 3) Limit output to a specific set of energies.

Experiment Procedure

Utilizing the EPICS2017 library of EpiXS,

- | | | |
|----------|--|---------|
| 1 | Identify the most effective glass that could serve as a superior alternative to lead-based glasses, specifically in terms of its ability to attenuate gamma radiation. | 6.0 pts |
|----------|--|---------|

- | | | |
|----------|--|---------|
| 2 | <p>Consider the following:</p> <ul style="list-style-type: none"> • The μ/ρ for lead-based glass at an energy level of 1.173 MeV is approximately $0.0625 \text{ cm}^2/\text{g}$. • The densities of the lead-based glass and the most effective glass (as referred to in a previous question) are 11.0 g/cm^3 and 8.0 g/cm^3, respectively. <p>With these assumptions,</p> <ol style="list-style-type: none"> a. Determine the thickness of the most effective glass that would provide the same level of radiation protection as a | 2.0 pts |
|----------|--|---------|

10 cm thick layer of lead-based glass at an energy level of 1.173 MeV.

- b. Determine the thickness of the most effective glass that would effectively block 90% of the gamma radiation.

- 3** Consider replacing lead-based glass with a composite of two materials, *Glass A* and *Glass B*. These glasses have unique properties including different μ/ρ (known values obtained from EpiXS), densities (ρ_A for *Glass A*, ρ_B for *Glass B*), and thicknesses (x_A for *Glass A*, x_B for *Glass B*). Derive an expression for the intensity of a photon beam after passing through both glasses. 2.0 pts

Q6. Radiation Damage - Computational (10 pts)

Experiment Guide

A. Experiment background/ theory

Satellites and spacecrafts are equipped with electronic components, such as microprocessors, memory chips, and sensors to perform various tasks like communication, data collection, and navigation. While in space, these electronic components can be exposed to alpha radiation, primarily in the form of alpha particles originating from solar wind and cosmic rays. Alpha particles, which account for ~10% of cosmic rays, may penetrate the spacecraft's protective shielding to some extent. When alpha particles interact with the semiconductor materials in these electronic components, they can deposit energy within the semiconductor lattice. This can lead to the creation of electron-hole pairs and introduce charge carriers that may interfere with the proper functioning of the semiconductor devices. The energy deposited by alpha particles can cause transient or permanent changes in the device's electrical characteristics.

In this experiment, you will use the SRIM (Stopping and Range of Ions in Matter) software to investigate the interaction of alpha particles with the following semiconductor materials:

Semiconductor	Space applications	Density (g/cm ³)
Silicon (Si)	Microprocessors, memory chips, sensors	2.32
Galium Arsenide (GaAs)	Radio-frequency (RF) and microwave devices for communication applications	5.32

B. Software Description

SRIM (Stopping and Range of Ions in Matter) is a widely used software package designed for simulating interaction of charged particles with matter. The software, which is developed by James Ziegler and collaborators, is primarily used to simulate the penetration depth, energy loss, and scattering of ions as they pass through a user-defined material. SRIM has been utilized in various fields of research and technology, particularly in nuclear physics, materials science, and semiconductor engineering. While SRIM is a powerful tool, it is important to note that it provides theoretical predictions based on models and databases. Whenever possible, users should validate their simulations through experimental data.

You can get the software and its full documentation through this link:
<http://www.srim.org/>

Key features of the SRIM software are provided below:

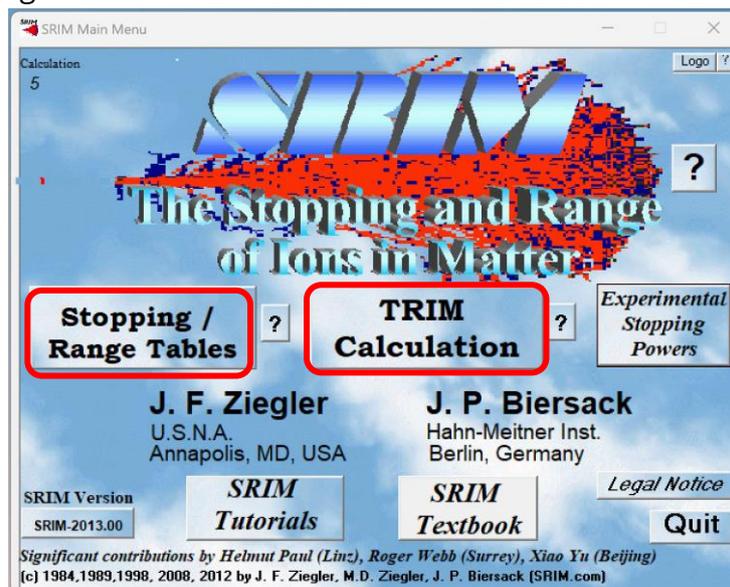
1. SRIM can calculate the range of ions in a material (stopping range) and the energy loss of ions as they traverse the material.
2. It can predict the distribution of atomic displacements and damage that ions induce in the target material. This is crucial for understanding radiation damage and material modification.
3. It includes a comprehensive database of material properties, allowing users to select from a wide range of materials for simulations.
4. Users can generate plots showing the range of ions versus their energy.
5. It can simulate the behavior of ions in a material, including backscattering, straggle (or uncertainty in the final position or range of ions), and other scattering effects.

C. Software Guide

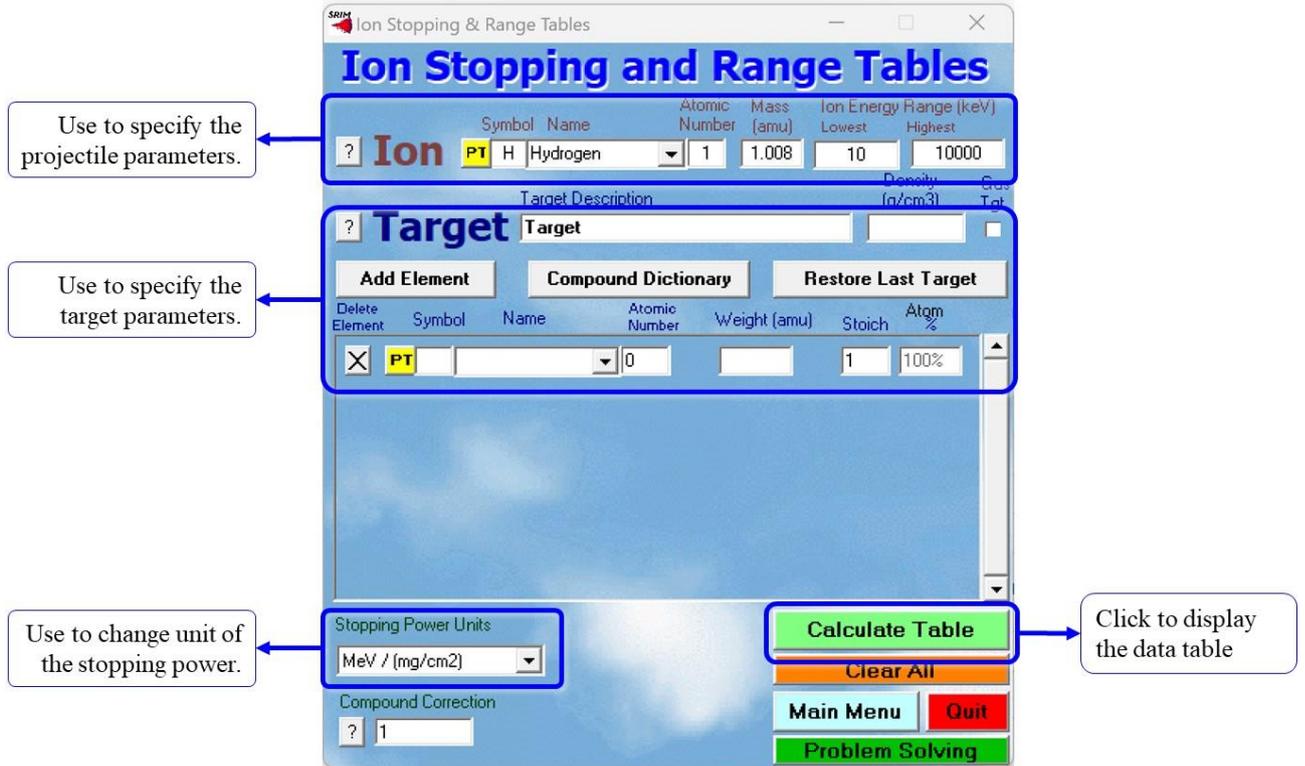
The SRIM software can be launched by tapping on the icon below:



The interface for the main menu is shown below. For this experiment, you will use both the “Stopping/Range Tables” button and the “TRIM Calculation” button.



The setup window of the “Stopping/Range Tables” module of the software is shown below. Features that will be used for this experiment are highlighted.



The setup window of the “TRIM” module of the software is shown below. The module has several features but for this experiment only the highlighted parts will be used.

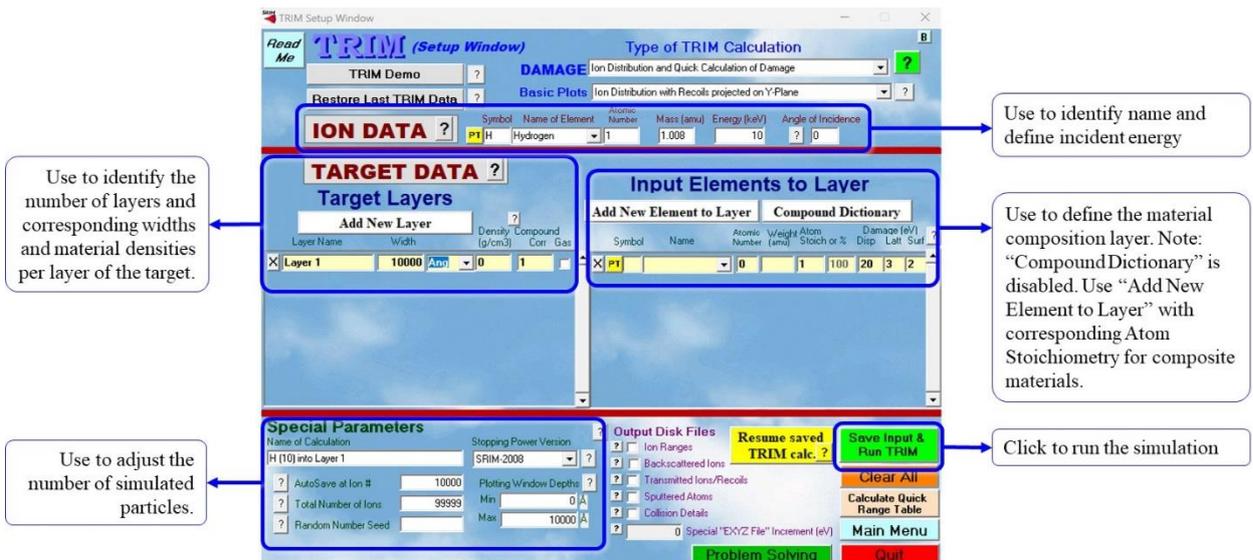
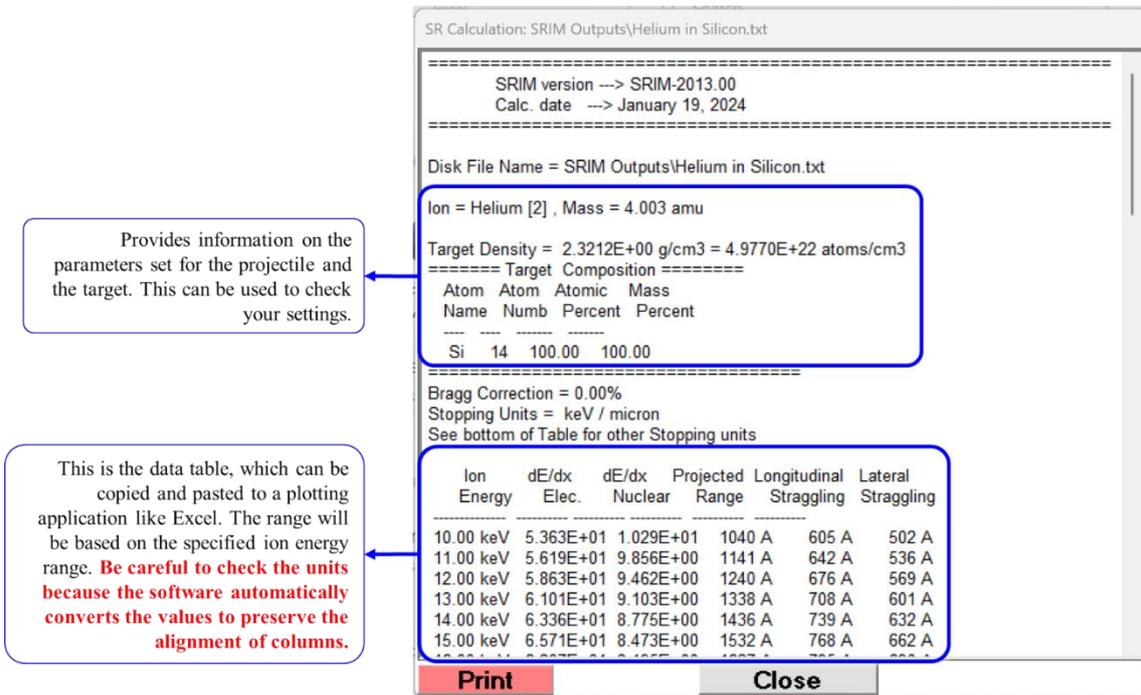


Figure 2. SRIM User Interface

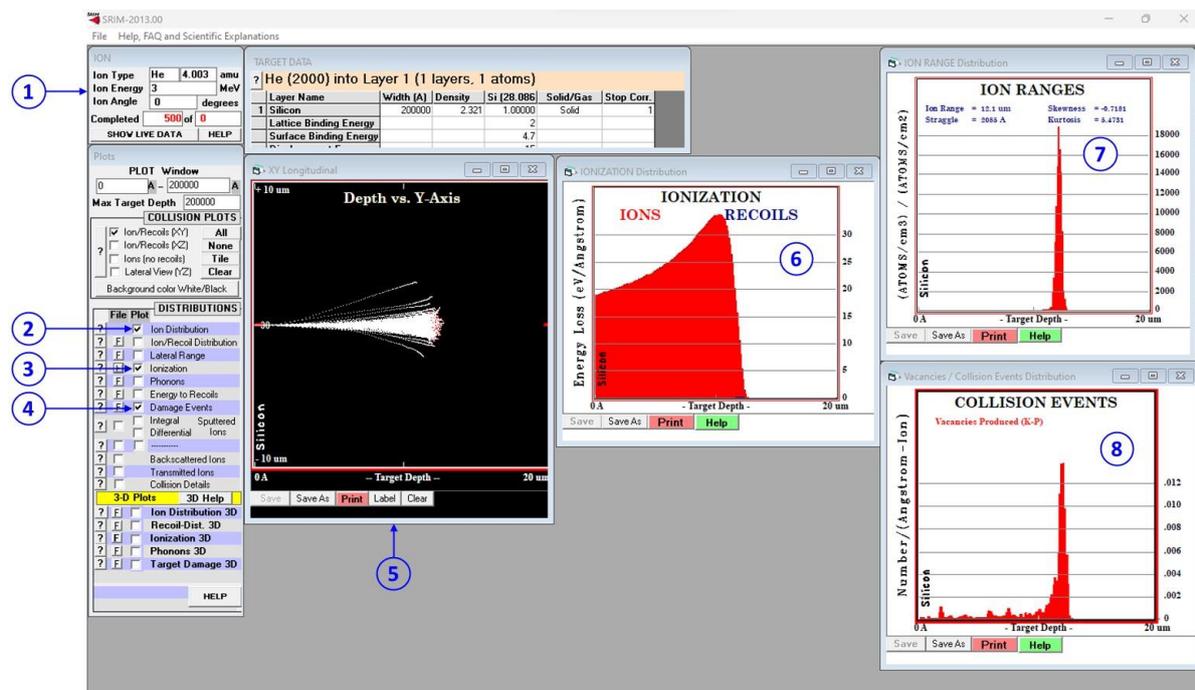
Note: You can click on the “?” button to get more information about the features of the simulator.

Software outputs

The sample output of the “Stopping/Range Tables” module is a data table. A sample output is provided in the figure below.



The display window and the selected outputs for the “TRIM” module is shown below:



Where

- 1 – Displays the simulation setting.
- 2 – Toggle to display plot 7 (Ion distribution/range plot)
- 3 – Toggle to display plot 6 (Ionization plot)
- 4 – Toggle to display plot 8 (Damage/collision event plot)

Experiment Procedure

Part 1. Range of alpha particles (4.5 pts)

- a. Select the “Stopping/Range Tables” module of the SRIM software.
- b. Change the ion setting to Helium (He), to indicate an alpha particle.
- c. Adjust the lowest He ion energy to 2 MeV.
- d. Change the target setting to silicon (Si).
- e. Click the “Calculate Table” button.
- f. Record/copy the data provided by the software.
- g. Reset the software by clicking “Clear All” and repeat steps **b** to **f** for a gallium arsenide (GaAs) target. Make sure to click “Add Element” to account for both gallium (Ga) and arsenic (As) and to indicate the density as 5.32 g/cm³.

1.1 Record the alpha particle range for each semiconductor material in Table 1. Write your answers up to 2 decimal places. 1.0 pt

Table 1. Alpha particle range as a function of energy for Si and GaAs

Alpha particle energy, E_α (MeV)	Alpha particle range, R (microns)	
	Silicon (Si)	Gallium arsenide (GaAs)
2.0		
4.0		
6.0		
8.0		
10.0		

1.2 Plot the alpha particle range as a function of its energy using the data from Table 1. Use a single plot for both semiconductors. You may use any plotting software. 1.0 pt

1.3 Derive an equation to express the relationship between the range (R) and incident energy (E_α) for alpha particles for each semiconductor. You may use the trendline feature of the plotting software that you are using. (*Hint: You may expect a 2nd order polynomial for the trendline*). Using the expression for the quadratic equation below: 1.5 pt

$$R = aE_\alpha^2 + bE_\alpha + c$$

Where a, b are the coefficients and c is a constant. Record a, b and c for both Si and GaAs in Table 2. Write the answers with 3 significant figures.

Table 2. Equation coefficients and constants for alpha particle range in Si and GaAs

Coefficients/ Constants	Value	
	Silicon (Si)	Gallium arsenide (GaAs)
a		
b		
c		

1.4 Cosmic alpha rays can have energies from 1 GeV up to a few TeV. But the particles can be slowed down by other materials in the spacecraft before reaching the semiconductor in an electronic component. Suppose alpha particles have been slowed down to 50 MeV energy before reaching the semiconductors, use the equations derived from 1.3 to estimate the range of the alpha particles in each of the semiconductor material. Write your answers up to 2 decimal places. 1.0 pt

Part 2. Radiation damage (5.5 pts)

- Select the "TRIM" module of the SRIM software.
- Change the number of ions in the "Special Parameters" section to 2000.

- c. Change the ion data to helium (He) with 3 MeV energy.
- d. Adjust the target data into 15 micron silicon (Si).
- e. Run the simulation.
- f. After the simulation, click on the toggles to display plots 6, 7, and 8. Refer to the guide for the SRIM outputs for reference.
- g. Take a screen capture of the software display to serve as your reference for answering the following questions.
- h. Reset the software by clicking "Clear All" and repeat steps **b** to **g** for a gallium arsenide (GaAs) target. Make sure to click "Add Element" to account for both gallium (Ga) and arsenic (As) and to indicate the density as 5.32 g/cm³.

2.1 Bragg peak is the point at which the energy deposited by the ions reaches a maximum value. Determine the depth at which the Bragg peak occurs for each semiconductor, for 3 MeV alpha particles.	0.5 pts
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2.2 In which semiconductor did the 3 MeV alpha particles reach a longer distance? Explain why based on the plots and the material characteristics.	1.0 pts
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One way to describe radiation damage or defect in a material is by estimating the amount of displaced atoms or vacancies that was caused by the incident radiation in the atomic structure of the target material.

2.3 At what depth was the maximum defect production observed for each semiconductor? How is this related to the Bragg peak?	0.5 pts
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2.5 Refer to plot 8 to answer the following questions:	
a. What are the maximum vacancies produced per cm-ion for each semiconductor?	0.5 pts
b. Calculate the atom density for Si and the molecular density for GaAs. The molar mass for the semiconductors are $M_{Si} =$	0.5 pts

28.0855 g/mol and $M_{GaAs} = 144.645$ g/mol. Avogadro's number is $N_A = 6.022 \times 10^{23}$ /mol.

- c. If the intensity of the incident 3 MeV cosmic alpha particles on each semiconductor is 5×10^{15} ions/ cm², calculate the number of stable vacancies per cm³ in each semiconductor if we assume that 98% of the damage is healed through annealing. 1.5 pts
- d. What percentage of the Si and GaAs targets were damaged? 0.5 pts

QUESTION-SYLLABUS MATRIX

Questions	Syllabus Topics						
	1	2	3	4	5	6	7
1. Locating an orphan source		■				■	
2. Gamma spectrometry		■					
3. Half-life experiment		■					
4. Half-life experiment (Computational)		■					
5. Gamma shielding (Computational)		■					■
6. Radiation damage (Computational)		■					■

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QUESTION FEEDBACK

Send your feedback on the questions through the link or QR code below:

<https://bit.ly/INSOProblems>



See you at the
First International Nuclear Science Olympiad
in the Philippines!

