KEY OF PREPARATORY PROBLEMS

for the

First International Nuclear Science Olympiad (1st INSO)

EXPERIMENTAL

Answer key to the preparatory problems will be released in April 2024.

INSO
International Nuclear Science Olympiad

Key of 1st INSO Preparatory Problems

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CONTENT

Q1. LOCATING AN ORPHAN SOURCE (10 pts)

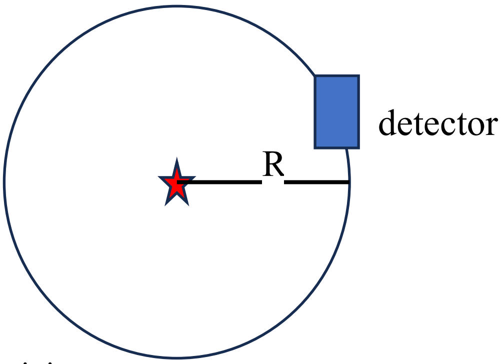
1.

We assume a calibration source, so it produces 1 radiation/decay.

At distance R, these radiations will be distributed in a sphere.

Given that S_0 represents the source term and the area of the sphere is $4\pi R^2$, it is fair to assume that at distance R, the flux (ϕ) is roughly.

$$\phi = \frac{S_0}{4\pi R^2}$$



At the specific spot in the sphere,

1) Not all the particles will be emitted at R
2) More than 1 radiation can be emitted per activity
3) Solid angle of detectors can survey for different geometry and types.
4) The conservation of particles into counts in detectors is not perfect, as detectors may exhibit inefficiencies, leading to the loss of particles.

It is convenient to combine all these functions into a single variable using the detector efficiency, ε

Thus, $c = \frac{\varepsilon S_0}{4\pi R^2}$

Where the flux (ϕ) is reflected by the count (c) and R can be expanded in terms of x and y.

*The experiment to be conducted by the students

*However, the use of the detector is necessary for student marking. Handling invisible radiation is a skill that students need to know.

1.	2 pts

2.

Standard error, $\Delta y = \frac{s}{\sqrt{N-1}}$

where; Δy is the standard error of the mean,

s is the sample standard deviation,

N is the sample size.

However, become,

$c = \frac{\varepsilon S_0}{4\pi R^2}$

Thus $(\frac{\Delta c}{c})^2 = (\frac{\Delta\varepsilon}{\varepsilon})^2 + (\frac{2\Delta R}{R})^2$

If the ε is assumed that be small so,

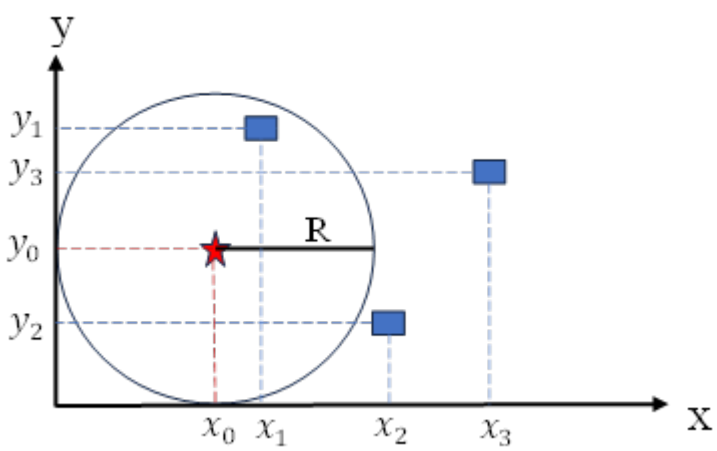
the maximum uncertainty will come from an error in R (position), which

$$R^2 = (x - x_0)^2 + (y - y_0)^2$$

2.	$R^2 = (x - x_0)^2 + (y - y_0)^2$	1 pts

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 pts)

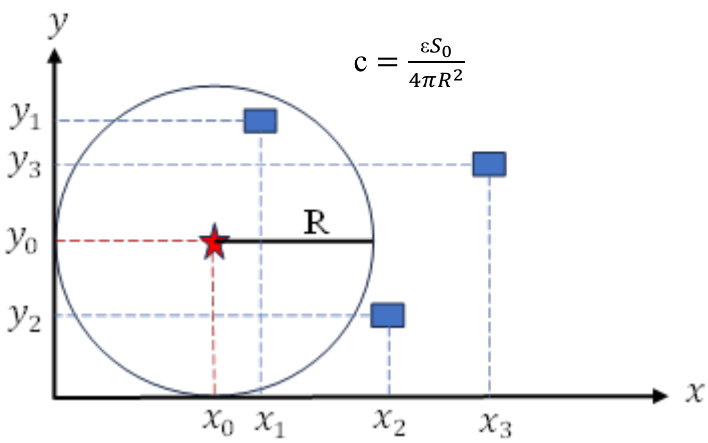


x (m)	y (m)	Counts/second

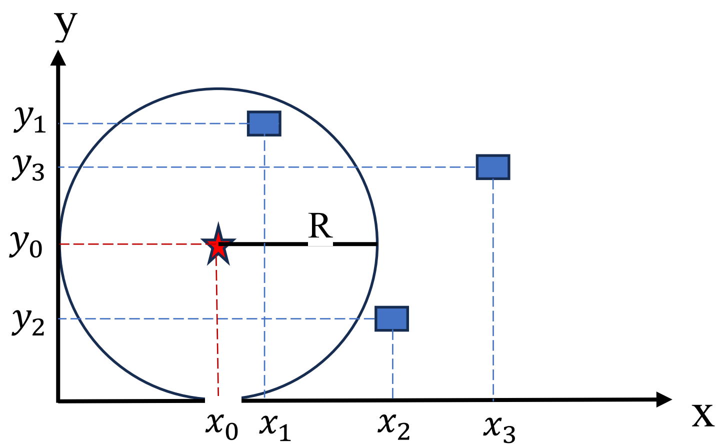
** If the survey meter is direction sensitive, only 2 locations for taking counts are needed. However, it is necessary to identify the direction with the strongest count. The location of the source is the point in which the vectors of the strongest counts from two measuring locations intersect.

3.	2 pts

4.



$$c_i = \frac{\varepsilon S_0}{4\pi} \frac{1}{(x_i - x_0)^2 + (y_i - y_0)^2}$$



4. $c_i = \frac{\varepsilon S_0}{4\pi} \frac{1}{(x_i - x_0)^2 + (y_i - y_0)^2}$	2 pts

5.

solution 1 Given that, each count for each x and y is measured.

$$c_i = \frac{\varepsilon S_0}{4\pi} \frac{1}{(x_i - x_0)^2 + (y_i - y_0)^2}$$

$$c_1 = \frac{\varepsilon S_0}{4\pi} \frac{1}{(x_1 - x_0)^2 + (y_1 - y_0)^2}$$

$$c_2 = \frac{\varepsilon S_0}{4\pi} \frac{1}{(x_2 - x_0)^2 + (y_2 - y_0)^2}$$

$$c_3 = \frac{\varepsilon S_0}{4\pi} \frac{1}{(x_3 - x_0)^2 + (y_3 - y_0)^2}$$

solution 2

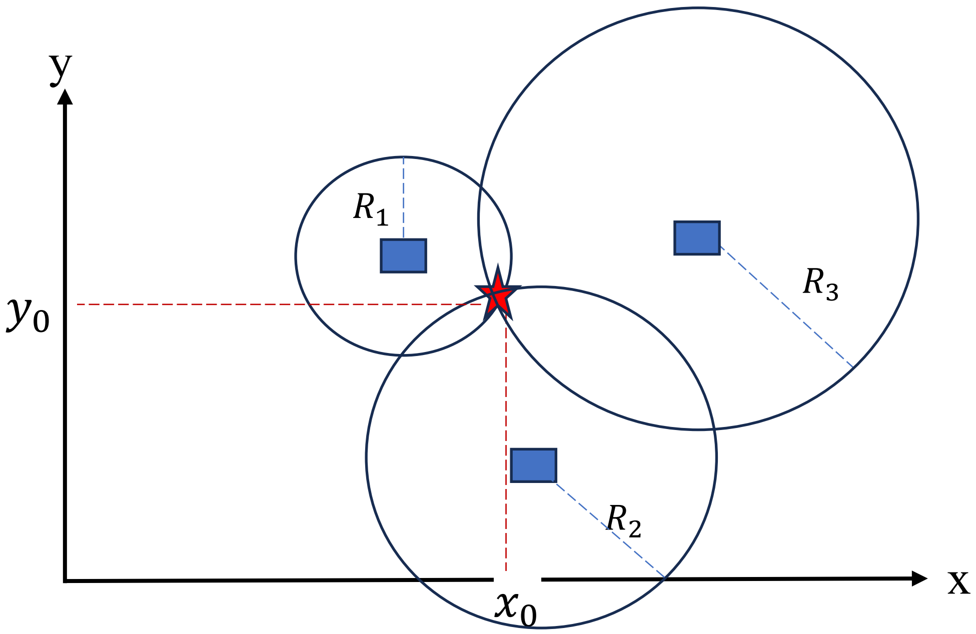
Given that, each count for each x and y is measured.

From $$c = \frac{\varepsilon S_0}{4\pi R^2}$$

Given $$\alpha = \frac{\varepsilon S_0}{4\pi} = 100$$

Thus $$R_1^2 = \frac{\alpha}{c_1} = \frac{100}{100},\quad R_2^2 = \frac{\alpha}{c_1} = \frac{100}{25},\quad R_3^2 = \frac{\alpha}{c_1} = \frac{100}{10}$$

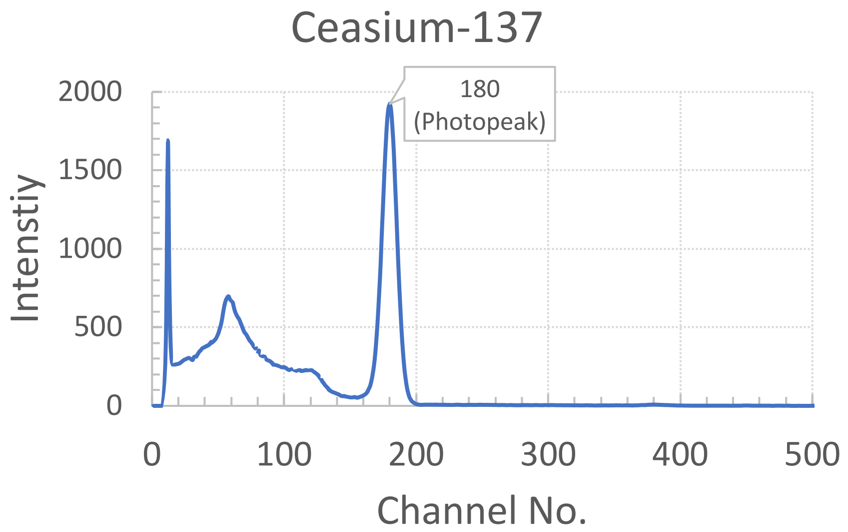
$$R_1 = 1,\quad R_2 = 2,\quad R_3 = 3.16$$



Q2. Gamma Spectrometry (10 pts)

1.1

1.1 0.5 pts



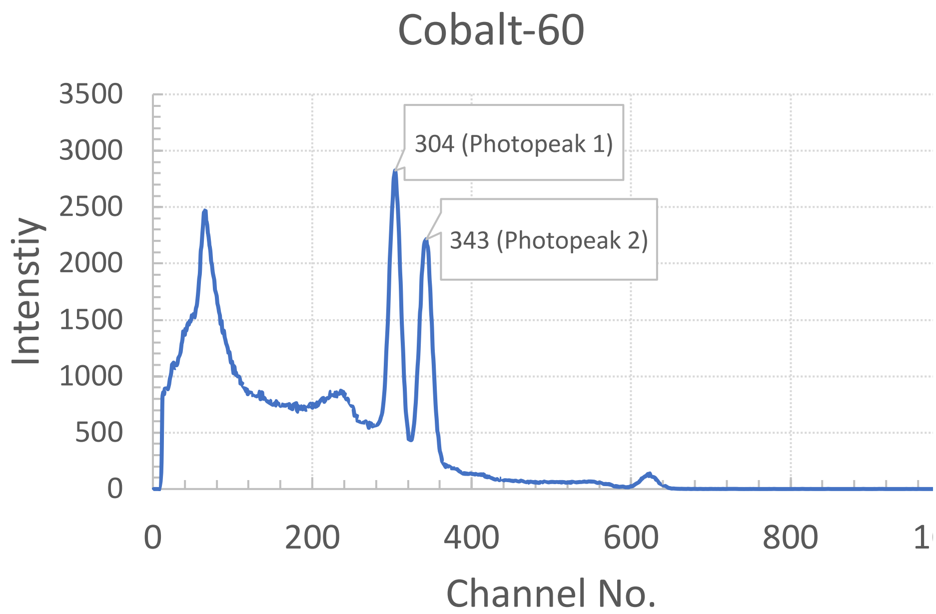


Table 1.1 Energy Calibration

Event	Energy (keV)	Peak Channel Number
Cs-137 photopeak	661.6	**180**
Co-60 photopeak (1)	1173.2	**304**
Co-60 photopeak (2)	1332.5	**343**

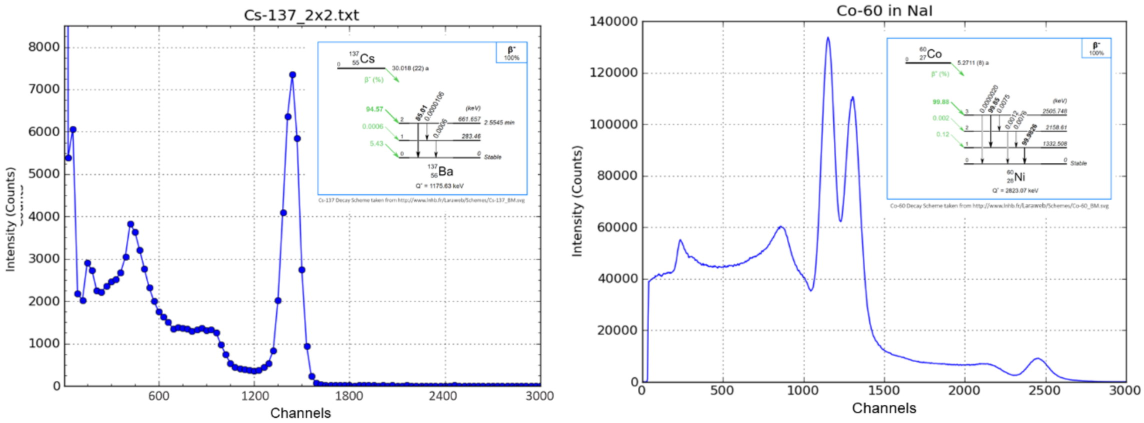
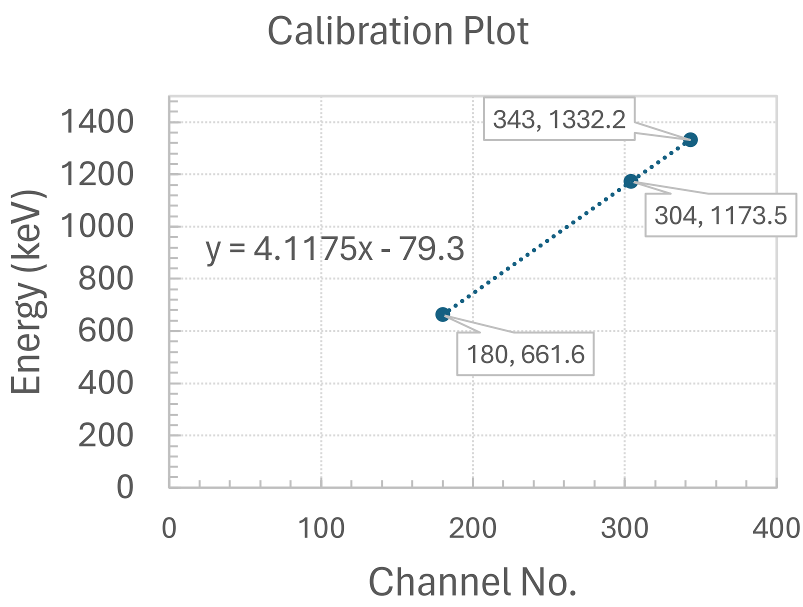


Figure 1. Sample gamma spectra for Cs-137 and Co-60. Decay schemes in inset photo.

1.2

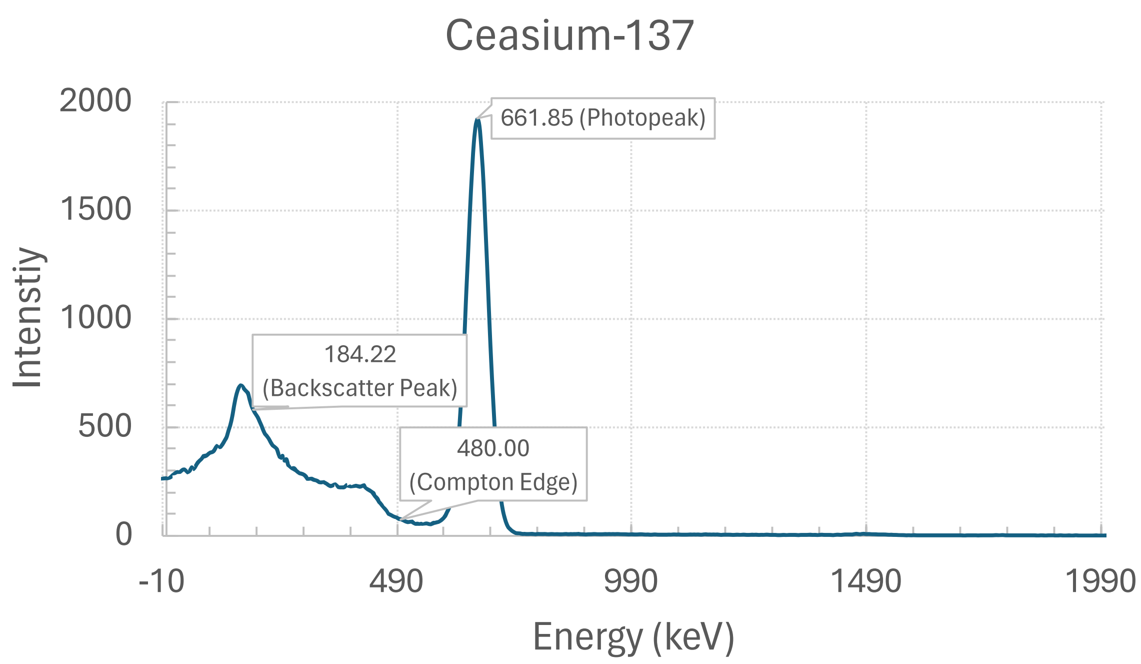
1.2 **Energy = 4.1175*Channel No. – 79.3** 1.0 pt

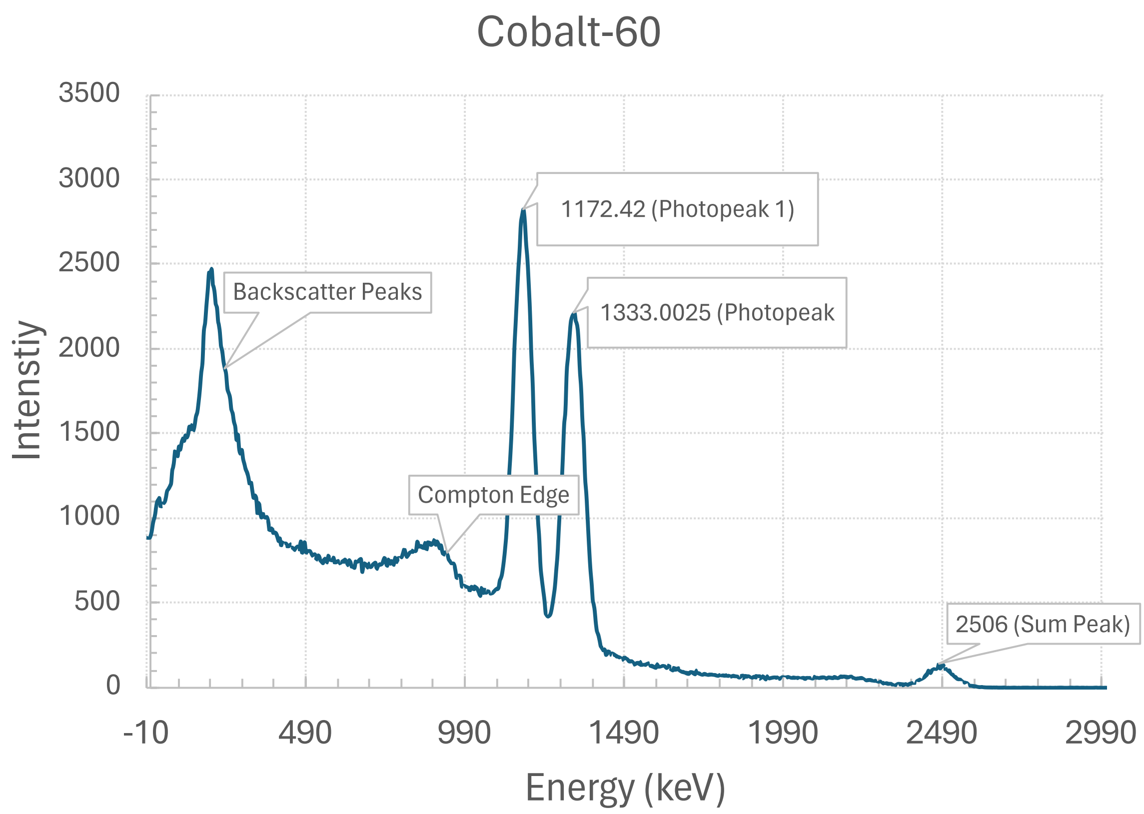


Part 2. Identify Spectrum Artefacts (1.0 pt)

2.1

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. A backscatter peak when gamma-rays hits a material around the detector and scattered back into the detector, usually at lower energies. 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 **Answer:** 1.0 pt

Artefact / Event	Energy (keV)	Peak Channel Number
Compton Edge of Co-60	**950 – 1120**	**286 – 248**
Compton Edge of Cs-137	**480**	**130 – 142**
Backscatter of Co-60	**200 – 220**	**75 – 65**
Backscatter of Cs-137	**184**	**60 – 68**
Sum peak of Co-60	**2505**	**620 – 636**

Part 3. Obtain efficiency curve (4.5 pts)

3.1

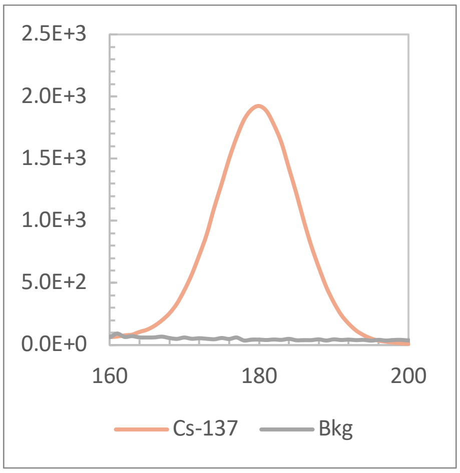
The spectrum raw file contains all the information about the analysis. The 'MEAS TIM:' in the spectrum header contains two pieces of information – the live time or the machine counting time and the real time or the clock time accounting for the dead time. The operator can set which of the two is to be used as PRESET TIME. For this run, the LT was used based on the information given in the footer of the spectrum.

3.1 **Answer:** 0.5 pts

File	Counting time (s)	Date of Counting
Cs-137.txt	1200	31 May 2023
Co-60.txt	1200	31 May 2023

3.2

As with other spectrometry techniques, the integral area under the curve is related to the number of particles that are being detected. A photopeak defined by a region of interest (ROI) describes the number of photons that interacted with the detector by photoelectric effect. The net area is the total counts from the source spectrum photopeak less that of the background within the given ROI.



Nuclide	Photopeak (keV)	Gross Area	Unc_G	Background	Unc_B
Cs-137	661.6	27,159	165	1,939	44
Co-60	1173.5	58,019	241	966	31
	1332.2	48,843	221	877	30

3.2 **Answer:** 1.0 pt

Nuclide	Photopeak (keV)	Net Area	Uncertainty
Cs-137	661.6	**25,220**	171
Co-60	1173.5	**57,053**	223
	1332.2	**47,966**	171

3.3

Table 2. Source Description for Efficiency Calibration

Radionuclide	Energy (keV)	Half-life, T1/2 (year)	Emission Probability (%)	Activity (uCi)	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%		

In gamma spectrometry, we relate the photopeak area in our spectrum to the amount of radioactivity of the source. For this, we need to perform full (or photopeak) energy peak efficiency. The Full-Energy Peak Efficiency Calibration gives the ratio of the photopeak intensity (in counts per second) to the number of gamma-rays emitted per second by the source (activity × gamma emission probability). This also takes into account the amount of photons that were not detected. Efficiency is in units of counts/disintegration and is obtained using Equation 1.

Efficiency = Activity / (Counts × emission probability) (Equation 1)

Note that efficiency calibration is geometry dependent. The geometry of the calibration source and sample to be analyzed is assumed to be similar for this problem solution. The activity needs to be corrected for the decay and expressed in units of decays/disintegration. The activity during the time of calibration is to be used to calculate for the efficiency with the relationship given in Equation 1.

3.3 **Answer:** 2.0 pts

Efficiency = disintegration/s / (Counts/s × emission probability (%))

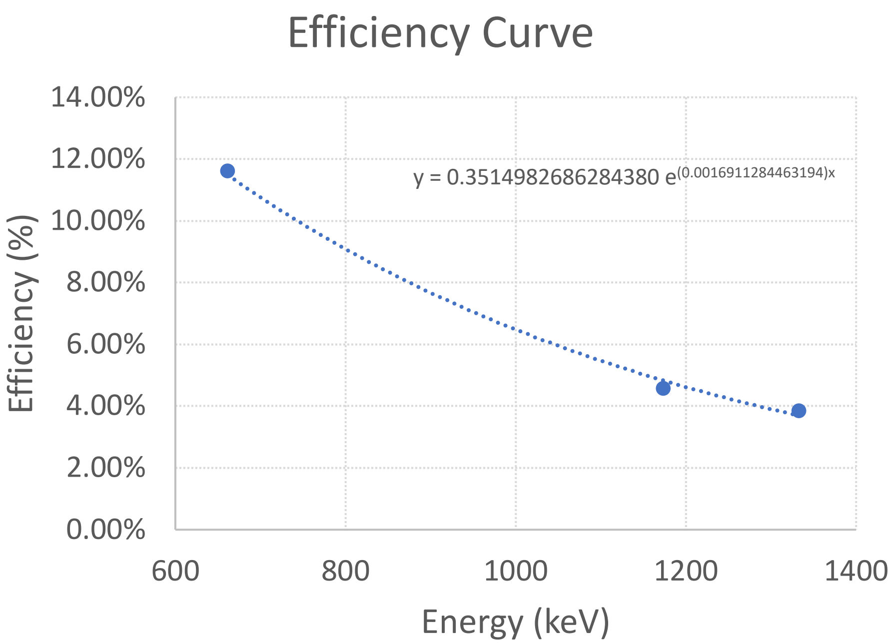
Nuclide	Corrected Activity (Bq)	Efficiency (%)	Unc
Cs-137	212.37	**17.37%**	0.0032%
Co-60	1039.42	**5.50%**	0.0011%
	1039.42	**3.94%**	0.00077%

3.4

The efficiency curve is fitted in an exponential fit.

3.4 1.0 pt

Answer:



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

4.1

The net area of each of the In-116m peaks is taken from the gross area subtracted to the background area within the same given ROI.

4.1 **Answer:** 1.0 pt

Photopeak (keV)	Peak ROI Left	Peak ROI Right	Net Area	Uncertainty
416.9	134	165	**29266040**	5410
1097.28	337	388	**25970561**	5096
1293.56	395	449	**26281785**	5126

4.2

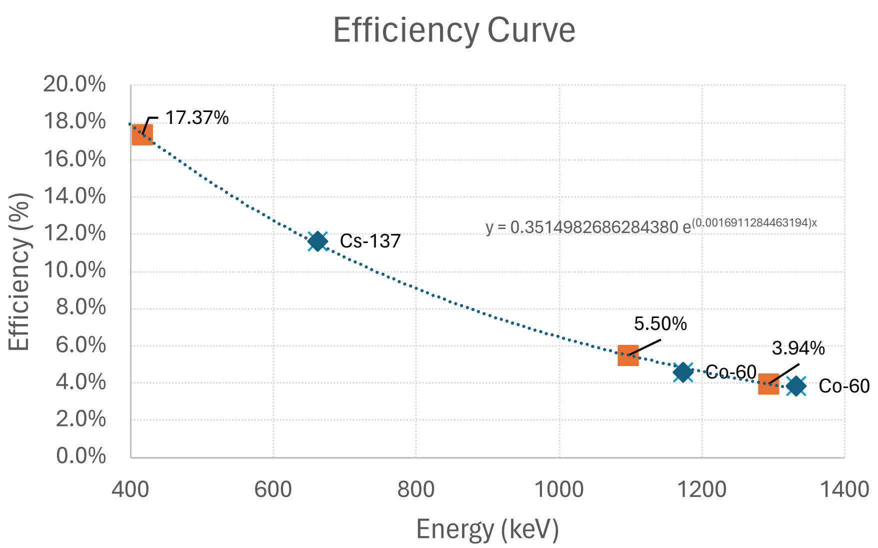


Table 3. In-116m Data

Radionuclide	Energy (keV)	Half-life, $T_{1/2}$	Emission Probability (%)
In-116m	162.39	2.18 sec	37.2%
	416.90	54.29 min	27.2%
	1097.28		58.5%
	1293.56		84.8%

4.2 **Answer:** 0.5 pts

Energy (keV)	Efficiency	Uncertainty
416.9	**17.37%**	0.0032%
1097.28	**5.50%**	0.0011%
1293.56	**3.94%**	0.00077%

4.3

The radioactivity of the Indium foil was estimated using the three photopeaks. However, the best estimate will be for the 1293.56 keV peak as it has the highest photon emission probability, nearest energy to the calibration sources used and minimal self-absorption in the indium foil compared to other gamma peaks. The 3% difference with the 1097keV peak also gives an acceptable result.

Activity, Bq = Net CPS, s^{-1} / efficiency(E_i), % x emission prob(E_i), %

4.3 **Answer:** 1.5 pts

	Energy (keV)	Activity (Bq)	Uncertainty
1	416.9	**516,276**	134
2	1097.28	**673,156**	186
3	1293.56	**654,948**	180

Q3. Half-life Experiment (10 pts)

1.1

Background counts: _(i) 54 __(ii) 53__(iii) 58___

Background counts (N_{bkg}): _________55______

Measurement Time Interval (T): _________100 s _________________

Background count rate ($r_{bkg} = N_{bkg}/T$): ______0.55 cps___________

1.1	Background count rate ($r_{bkg} = N_{bkg}/T$): ______0.55 cps____	0.5 pts

1.2

Source: I-116				
Time (t)	Counts (N)	Count rate ($r = N/T$)	Corrected count rate $r_{cor.} = r - r_{bkg}$	$ln\ (r_{cor.})$
1	2013	33.6	33.05	3.5
2	1921	32	31.45	3.4
3	1821	30.4	29.85	3.4
4	1871	31.2	30.65	3.4
5	1733	28.9	28.35	3.3
6	1837	30.6	30.05	3.4
7	1805	30.1	29.55	3.4
8	1668	27.8	27.25	3.3
9	1604	26.7	26.15	3.3
10	1646	27.4	26.85	3.3

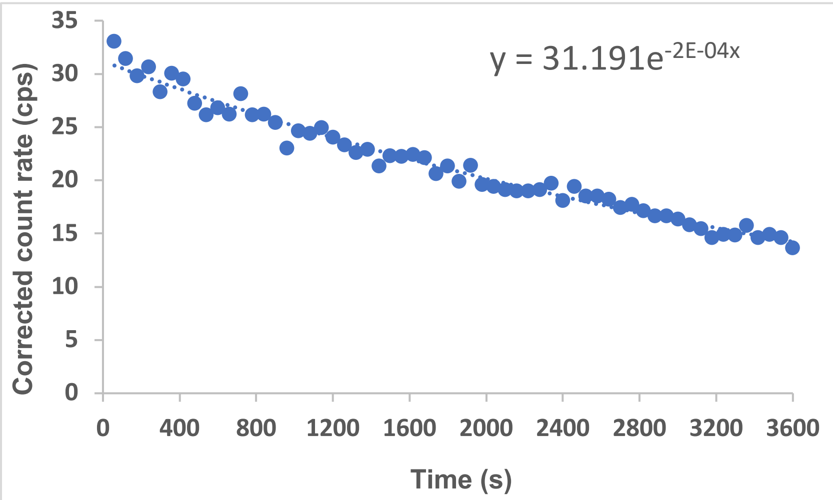
11	1605	26.8	26.25	3.3
12	1723	28.7	28.15	3.3
13	1599	26.7	26.15	3.3
14	1606	26.8	26.25	3.3
15	1560	26	25.45	3.2
16	1417	23.6	23.05	3.1
17	1512	25.2	24.65	3.2
18	1498	25	24.45	3.2
19	1529	25.5	24.95	3.2
20	1473	24.6	24.05	3.2
21	1436	23.9	23.35	3.2
22	1392	23.2	22.65	3.1
23	1407	23.5	22.95	3.1
24	1316	21.9	21.35	3.1
25	1373	22.9	22.35	3.1
26	1370	22.8	22.25	3.1
27	1379	23	22.45	3.1
28	1362	22.7	22.15	3.1
29	1272	21.2	20.65	3
30	1314	21.9	21.35	3.1
31	1232	20.5	19.95	3
32	1318	22	21.45	3.1
33	1210	20.2	19.65	3
34	1198	20	19.45	3

35	1184	19.7	19.15	3
36	1175	19.6	19.05	2.9
37	1175	19.6	19.05	2.9
38	1184	19.7	19.15	3
39	1218	20.3	19.75	3
40	1120	18.7	18.15	2.9
41	1198	20	19.45	3
42	1145	19.1	18.55	2.9
43	1143	19.1	18.55	2.9
44	1127	18.8	18.25	2.9
45	1078	18	17.45	2.9
46	1099	18.3	17.75	2.9
47	1060	17.7	17.15	2.8
48	1030	17.2	16.65	2.8
49	1034	17.2	16.65	2.8
50	1015	16.9	16.35	2.8
51	983	16.4	15.85	2.8
52	958	16	15.45	2.7
53	910	15.2	14.65	2.7
54	929	15.5	14.95	2.7
55	921	15.4	14.85	2.7
56	975	16.3	15.75	2.8
57	913	15.2	14.65	2.7
58	928	15.5	14.95	2.7

59	914	15.2	14.65	2.7
60	849	14.2	13.65	2.6

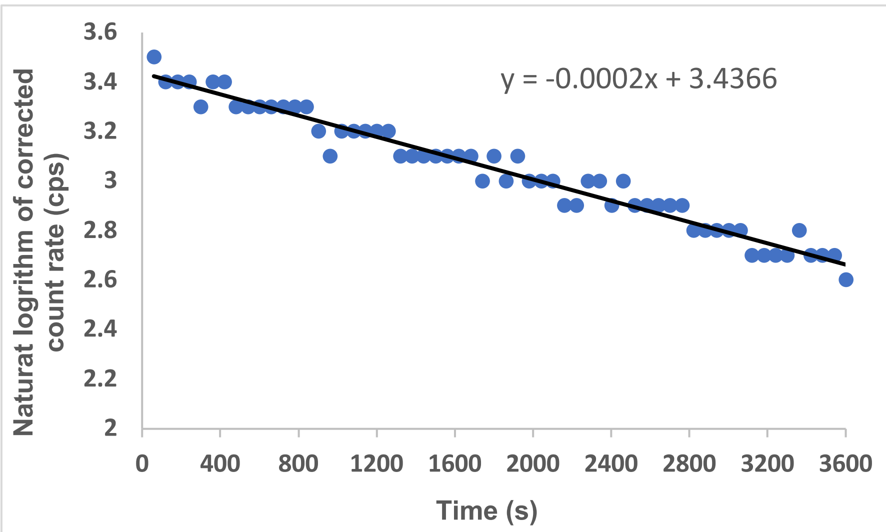
1.2	Observation data is shown above	1.5 pts

1.3



1.3	The estimated half-life is 3300 s (= 55 min)	2.0 pts

1.4



1.4	Graph between natural logarithm of count rate and time is shown above.	1.5 pts

1.5

The fitted straight line is; $\ln(r) = -0.0002\, t + 3.4366$

1.5	The fitted straight line is; $\ln(r) = -0.0002\, t + 3.4366$	2.0 pts

1.6

The slope of the fitted line is -0.0002 s-1. Using relation $m = -\lambda = -ln2/T_{1/2}$

$-0.0002 = -ln2/T_{\frac{1}{2}} \rightarrow T_{\frac{1}{2}} = 0.693/0.002 = 57.8$ min

1.6	$T_{\frac{1}{2}} = 0.693/0.002 = 57.8$ min	1.5 pts

1.7

The half life obtained in 1.6 has better accuracy because no human estimate is involved.

1.7	The half life obtained in 1.6 has better accuracy because no human estimate is involved.	1.0 pts

Q4. Half-life Experiment (10 pts)

Part 1. Calculation of activity (5 pts)

1.1

$$n = \frac{m_o}{M}$$

The initial mass (m_o) is given in the code as ($m_o = 0.1\ g$)

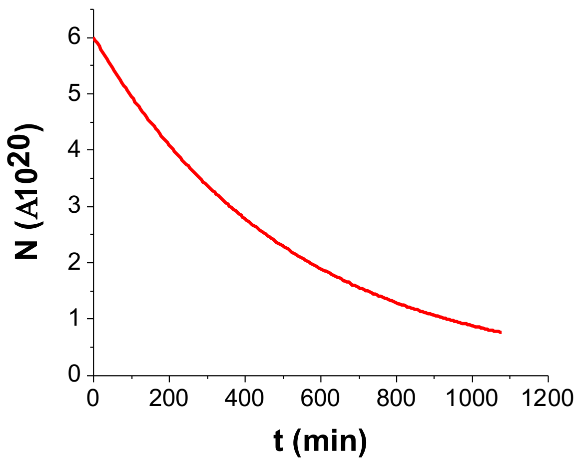
$$n = \frac{0.1}{98.9} = 1.01 \times 10^{-3}\ mol$$

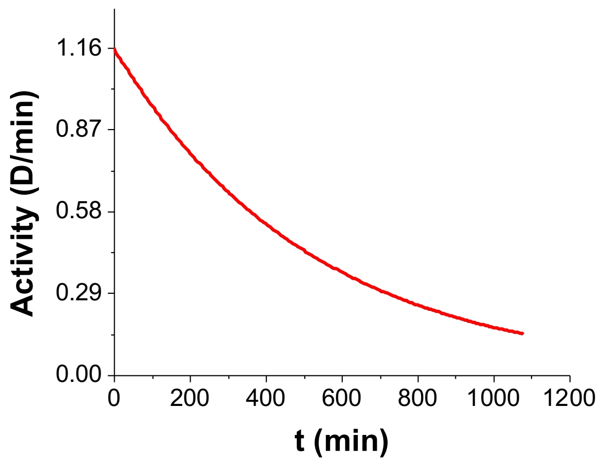
$$N_o = n \times Avogadro\ number$$

$$N_o = (1.01 \times 10^{-3})(6.022 \times 10^{23})$$

$$N_o \cong 6 \times 10^{20}\ atoms$$

1.2





1.3

	0.5hrs	1.5hrs	3hrs

Radioactivity (Bq)	1.82×10^{16}	1.62×10^{16}	1.36×10^{16}
Number of atoms (N)	5.66×10^{20}	5.05×10^{20}	4.24×10^{20}

1.4

$$A = \lambda N_o e^{-\lambda t}$$

$$A = \frac{\ln 2}{21600} \left(6 \times 10^{20}\right) e^{-\frac{\ln 2}{21600} \times 72000}$$

$$A = 1.91 \times 10^{15}\ Bq$$

$$A = \frac{1.91 \times 10^{15}}{3.7 \times 10^{10}} = 51.63 \times 10^{3}\ Ci$$

By this time the activity reduced by:

$$\frac{1.91 \times 10^{15}}{1.93 \times 10^{16}} \times 100\% = 9.89\ \%$$

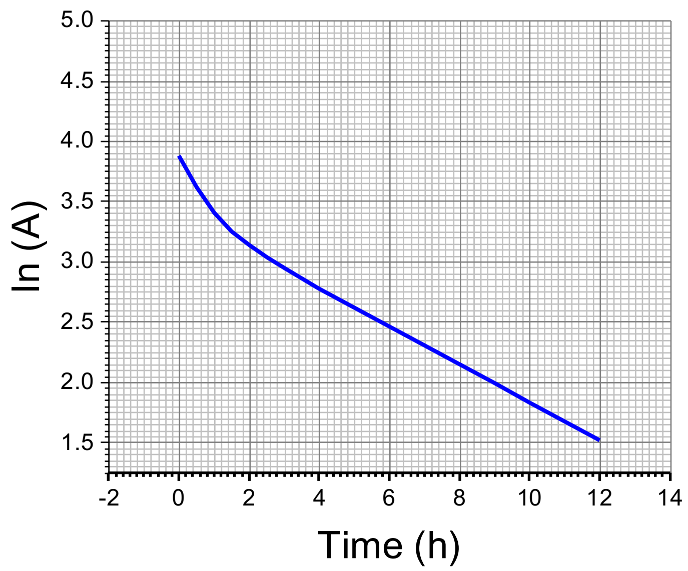
Part 2. Activity of a mixture (5 pts)

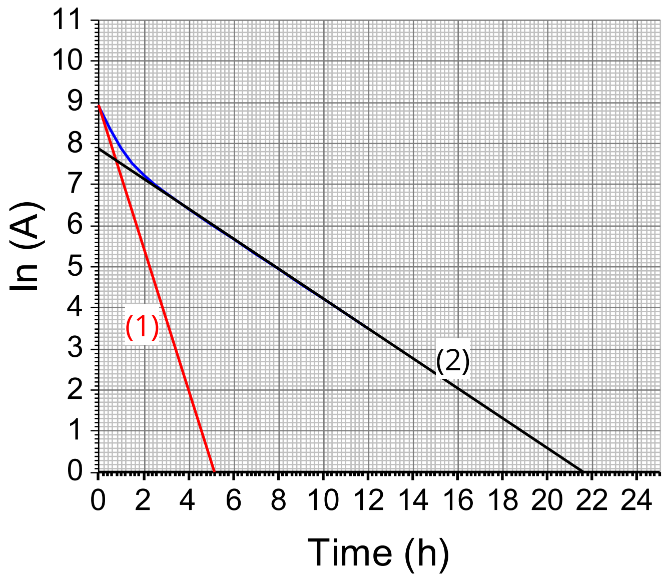
2.1

We need to calculate ($\ln A$) in order to know how many samples in the mixture.

Time (h)	Decays/s	$\ln A$
0	7500	8.92266
0.5	4120	8.32361
1	2570	7.85166
1.5	1790	7.48997
2	1350	7.20786
2.5	1070	6.97541
3	872	6.77079
4	596	6.39024
5	414	6.02587
6	288	5.66296
7	201	5.3033
8	140	4.94164
9	98	4.58497
10	68	4.21951
12	33	3.49651

Then plotting $\ln A$ verses time. It is clear that we can fit the graph into 2 linear equations.





From the fitting, **there are two radioactive samples** in the mixture.

2.2

Half-life calculations:
From the fitting, there are two linear equations as follows.

$$A = \lambda N_o \, e^{-\lambda t}$$

$$\frac{A}{\lambda N_o} = e^{-\lambda t}$$

$$\ln\left(\frac{A}{\lambda N_o}\right) = -\lambda t$$

$$\ln A = \ln(\lambda N_o) - \lambda t$$

($\ln A \rightarrow y$; $\ln(\lambda N_o) \rightarrow$ Intercept; $t \rightarrow x$; $-\lambda \rightarrow$ Slope)

Slope (1) $= \frac{0-8.9}{5.15-0} = -1.73 \implies \lambda_1 = 1.73\ h^{-1} \implies$ $\boxed{T_{\frac{1}{2}}(1) = 0.4\ h}$

Slope (2) $= \frac{0-7.8}{3.2-0} = -0.361 \implies \lambda_2 = 0.361\ h^{-1} \implies$ $\boxed{T_{\frac{1}{2}}(2) = 1.92\ h}$

2.3

From the linear equations, the intercept in the y-axis equals to $\ln(\lambda N_o)$
Then, for the first sample: $\ln(\lambda_1 N_{1o}) = 8.9$

$$N_{1o} = \frac{1}{\lambda_1} e^{8.9} = \frac{T_1}{\ln 2} e^{8.9} = \frac{0.4\times 3600}{\ln 2} e^{8.9} = 1.52\times 10^{7} \text{ nuclei}$$

$$N_{2o} = \frac{1}{\lambda_2} e^{7.8} = \frac{T_2}{\ln 2} e^{7.8} = \frac{1.92\times 3600}{\ln 2} e^{7.8} = 2.43\times 10^{7} \text{ nuclei}$$

2.4

$$N_1 = N_{1o}\, e^{-\lambda_1 t} = 1.52 \times 10^7\, e^{-1.73\times 5} \cong 2662 \quad \text{nuclei}$$

$$N_2 = N_{2o}\, e^{-\lambda_2 t} = 2.43 \times 10^7\, e^{-0.361\times 5} \cong 4 \times 10^6 \quad \text{nuclei}$$

The number of shorter-lived nuclei is much less than the number of long-lived nuclei, which is expected.

Q5. Gamma Shielding - Computational (10 pts)

1.

Using the EPICS2017 library of EpiXS

Glass	Mass attenuation coefficient (cm^2/g) at 1.173 MeV
A	0.0565
B	0.0548
C	0.0558
D	0.0574
E	0.0602

1.	Glass E (highest μ/ρ)	6.0 pts

2.

$$I_{Pb} = I_E$$

$$I_o e^{-(\frac{\mu}{\rho})_{Pb}\rho_{Pb}x_{Pb}} = I_o e^{-(\frac{\mu}{\rho})_E\rho_E x_E}$$

$$x_E = \frac{(\frac{\mu}{\rho})_{Pb}\rho_{Pb}x_{Pb}}{(\frac{\mu}{\rho})_E\rho_E} = \frac{(0.0625)(11)(10)}{(0.0602\ )(8)} \approx 14.275\ cm$$

2.	14.275 cm	2.0 pts

3.

After passing through the Glass A

$$I_1 = I_o e^{-0.0565\rho_A x_A}$$

After passing through the Glass B

$$I = I_1 e^{-0.0548\rho_B x_B}$$

Then

$$I = I_o e^{-0.0565\rho_A x_A} e^{-0.0548\rho_B x_B} = I_o e^{-(0.0565\rho_A x_A + 0.0548\rho_B x_B)}$$

3.	$I = I_o e^{-0.0565\rho_A x_A} e^{-0.0548\rho_B x_B} = I_o e^{-(0.0565\rho_A x_A + 0.0548\rho_B x_B)}$	2.0 pts

Q6. Radiation Damage - Computational (10 pts)

Part 1. Range of alpha particles (4.5 pts)

1.1

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

1.1

1.0 pt
(0.1 pt per entry)

Alpha particle range, *R* (microns)	
Silicon (Si)	**Gallium arsenide (GaAs)**
7.27	5.9
17.76	13.24
31.86	22.66
49.21	34.01
69.69	47.15

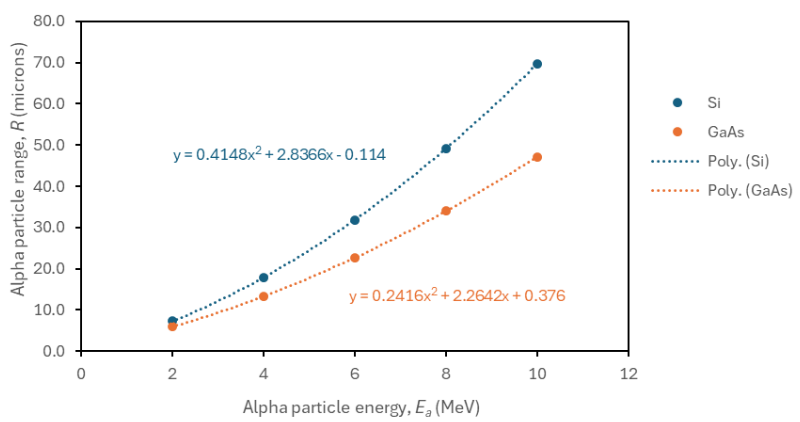
Note: Responses that are higher or lower by 5% compared to the provided answers here are acceptable.

1.2

Students may use any plotting software to obtain the plots and corresponding trendlines as presented below:

1.2 (a)

1.0 pt
(0.5 pts for each plot)



1.3 Given the equation below:

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

Students will be able to identify the parameters a, b, and c, using the trendlines obtained from **1.2**.

1.3

Coefficients/ Constants	Value	
	Si	GaAs
a	**0.415**	**0.242**
b	**2.837**	**2.263**
c	**0.144**	**0.376**

Note: Responses that are higher or lower by 5% *compared to the provided answers here are acceptable.*

1.5 pts *(0.25 pts per entry)*

1.4 Given the equation below:

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

For Si, the equation becomes:

$R = 0.415E_\alpha^2 + 2.837E_\alpha + 0.144$

The range of an alpha particle with incident energy of 50 MeV is then:

$R = 0.415(50\text{ MeV})^2 + 2.837(50\text{ MeV}) + 0.144 = \mathbf{1179.49\ microns}$ **or** $\mathbf{1.18\ mm}$

For GaAs:

$R = 0.242E_\alpha^2 + 2.263E_\alpha + 0.376$

The range of an alpha particle with incident energy of 50 MeV is then:

$R = 0.242(50\text{ MeV})^2 + 2.263(50\text{ MeV}) + 0.376 = \mathbf{718.53\ microns}$ **or** $\mathbf{0.72\ mm}$

1.4

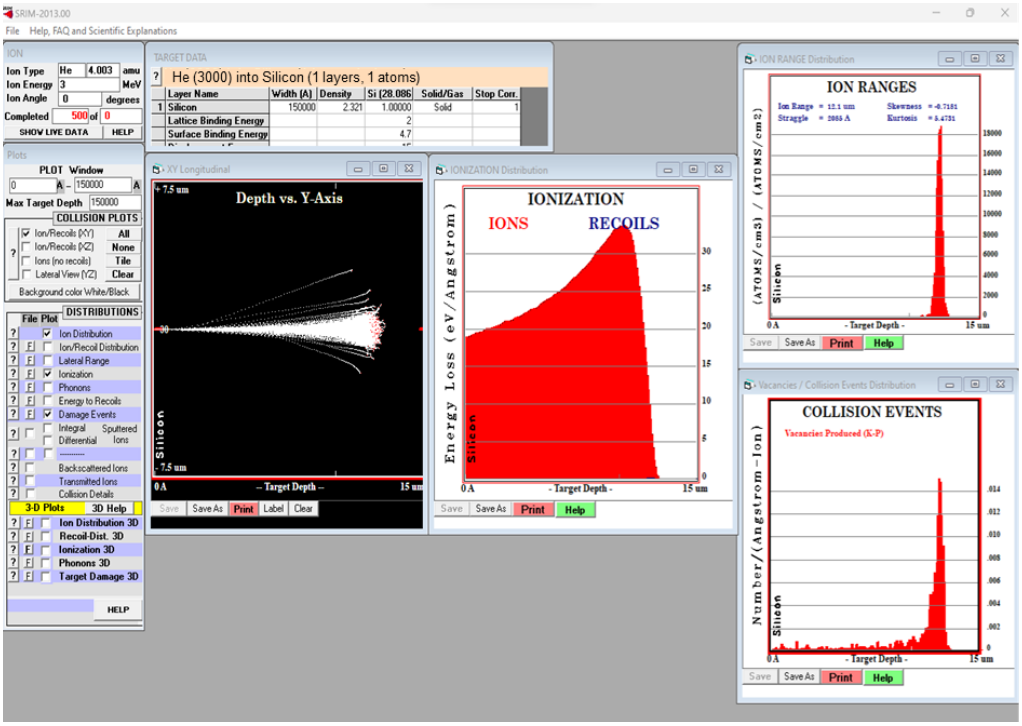
Silicon: 1179.49 microns or 1.18 mm
GaAs: 718.53 microns or 0.72 mm
Note: Responses that are higher or lower by 5% *compared to the provided answers here are acceptable.*

1.0 pts *(0.5 pts each)*

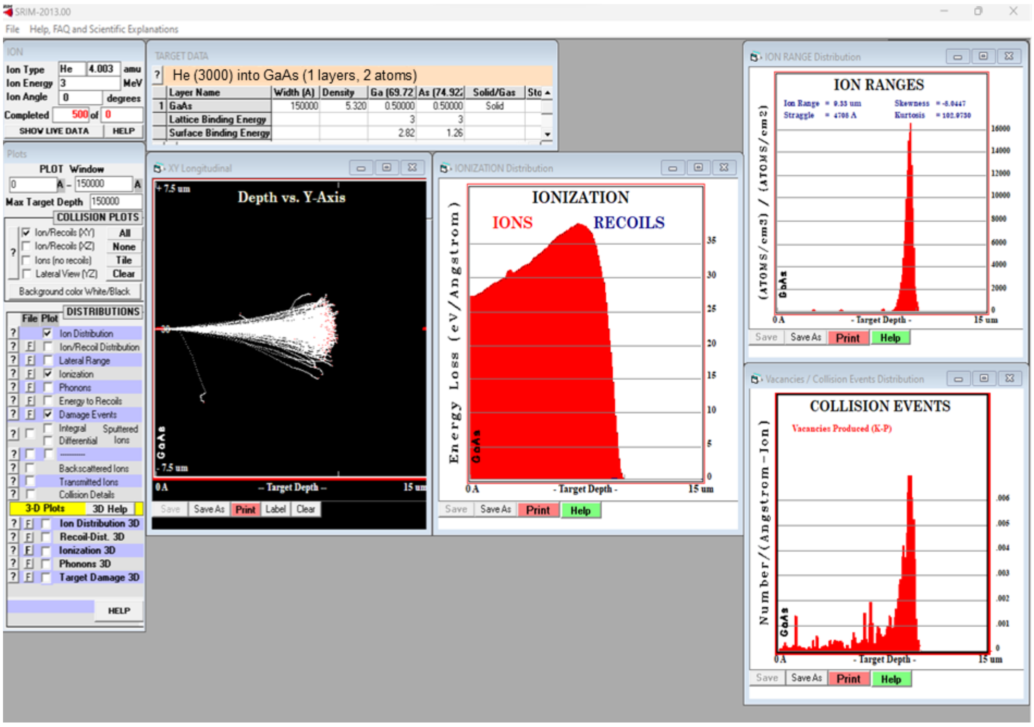
Part 2. Radiation damage (5.5 pts)

Screen captures of the simulations results, which will be the basis of the succeeding answers are presented below:

For Silicon:



For GaAs:



2.1 Based on the simulation results, students should be able to identify the Bragg peak for the alpha particles as follows:

2.1	Silicon: ~12 microns GaAs: ~9 microns *Note: Responses that are higher or lower by 5% compared to the provided answers here are acceptable.*	0.5 pts *(0.25 pts each)*

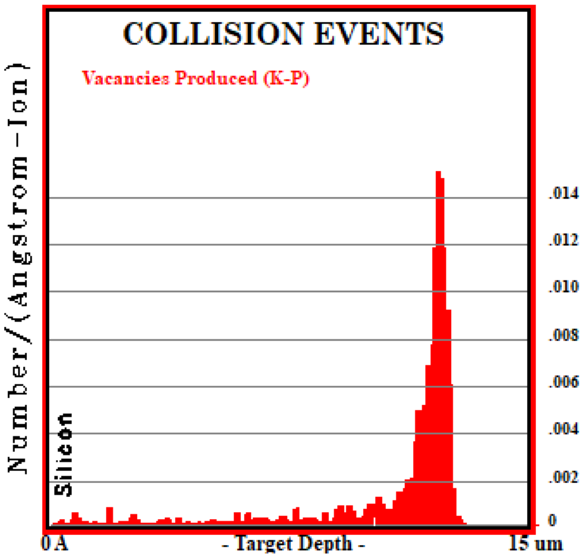
2.2	The plots show that the 3 MeV alpha particles reached **a longer (~28.6%) distance in silicon** compared to GaAs. This is mostly due to the **lower density of silicon**, which means that the incident alpha particles interact with **less target particles per unit distance** they traverse, and therefore can reach longer distances before losing all their energies.	1.0 pt *(Highlighted information are necessary to obtain full marks for this question)*

2.3	The depth at which maximum defect was observed for **Si (~12 microns)** and for **GaAs (~9 microns)** is at the **same depth as the Bragg peak**. This is expected because the alpha particle	0.5 pts *(Highlighted information are necessary*

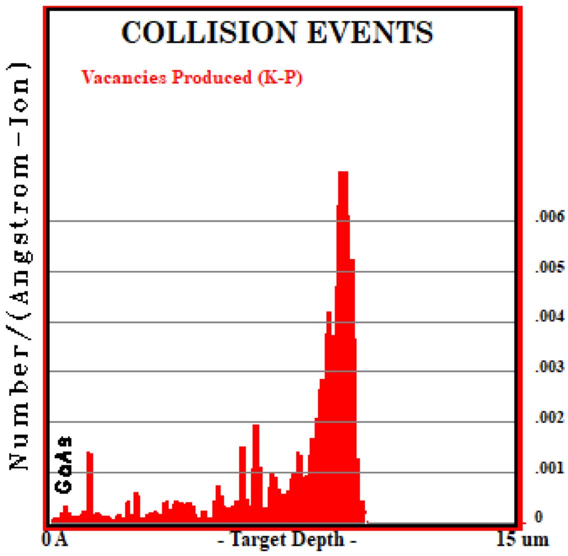
deposits most of its energy at the location of the Bragg peak.	*to obtain full marks for this question)*

For Question, 2.4, students are asked to refer to the following plots obtained from SRIM:

For Silicon:



For GaAs:



2.4 (a) Based on the plot, the maximum vacancies (V_m) are:

Silicon: $V_m = \frac{0.015 \text{ vac}}{\text{Å}-\text{Ion}}\left(\frac{1\times10^8 \text{Å}}{1 \text{ cm}}\right) = \mathbf{1.50 \times 10^6 \text{ vac/cm} - \text{ion}}$

GaAs: $V_m = \frac{0.007 \text{ vac}}{\text{Å}-\text{Ion}}\left(\frac{1\times10^8 \text{Å}}{1 \text{ cm}}\right) = \mathbf{7.00 \times 10^5 \text{ vac/cm} - \text{ion}}$

2.4 (a)	Silicon: $V_m = 1.50 \times 10^6$ vac/cm − ion Ga-As: $V_m = 7.00 \times 10^5$ vac/cm − ion	0.5 pts *(0.25 pts each)*

2.4 (b) The atom density is calculated using $N = \frac{\rho N_A}{M}$

Silicon: $N = \frac{(2.32 \text{ g/cm}^3)(6.022\times10^{23}/\text{mol})}{28.0855 \text{ g/mol}} = \mathbf{4.974 \times 10^{22} \text{cm}^{-3}}$

GaAs: $N = \frac{(5.32 \text{ g/cm}^3)(6.022\times10^{23}/\text{mol})}{144.465 \text{ g/mol}} = \mathbf{2.215 \times 10^{22} \text{cm}^{-3}}$

2.4 (b)	Silicon: $N = 4.974 \times 10^{22}\text{cm}^{-3}$ Ga-As: $N = 2.215 \times 10^{22}\text{cm}^{-3}$	0.5 pts *(0.25 pts each)*

2.4 (c) Stable vacancies V_s can be calculated from the percent damage ($\%D$), maximum vacancies (V_M)and beam intensity I as follows:

$$V_s = I \cdot \%D \cdot V_M$$

Given: $I = 5 \times 10^{15}$ ions/cm^2 and $\%D = 100\% - 98\% = 2\%$

Silicon: $V_s = (5 \times 10^{15}\ \text{ions/cm}^2)(0.02)(1.50 \times 10^6\ \text{vac/cm} - \text{ion}) = \mathbf{1.50 \times 10^{20} cm^{-3}}$

Ga-As: $V_s = \left(5 \times 10^{15} \frac{\text{ions}}{\text{cm}^2}\right)(0.02)\left(7.00 \times 10^5 \frac{\text{vac}}{\text{cm}} - \text{ion}\right) = \mathbf{7.00 \times 10^{19} cm^{-3}}$

2.4 (c)	Silicon: $1.50 \times 10^{20}\text{cm}^{-3}$ Ga-As: $7.00\times 10^{19}\text{cm}^{-3}$	1.5 pts *(0.75 pts each)*

2.4 (d) The percent target ($\%T$) of Si atoms and GaAs molecules that were damaged can be calculated from the stable vacancies (V_s) and the atom/molecule density (N_A) as follows:

$$\%T = \frac{V_s}{N}$$

Silicon: $\%T = \frac{1.50\times10^{20}\text{cm}^{-3}}{4.974\times10^{22}\text{cm}^{-3}} = \mathbf{0.30}\%$

GaAs: $\%T = \frac{7.00\times10^{19}\text{cm}^{-3}}{2.215\times10^{22}\text{cm}^{-3}} = \mathbf{0.32}\%$

2.4 (d)	Silicon: 0.302% Ga-As: 0.316%	1.5 pts *(0.75 pts each)*

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See you at the

First International Nuclear Science Olympiad

in the Philippines!

1st

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