Experiment 13N

FV 2/8/11

RADIOACTIVITY

MATERIALS: *(total amounts per lab)* small bottle of KCl; isogenerator kit; eluting solution; cobalt-60 gamma source; strontium-90 beta source; 1 Geiger counter; 2 Daedalon counters with probes; 2 white Geiger probe/absorber holders; 1 thin Al foil (#5); 2 Al plates; 1 plastic absorber; 2 Pb sheets; 4 Petri dishes; disposable gloves (for instructor); dissecting microscope.

PURPOSE: To determine the half-life of potassium-40 and barium-137m, and to determine the relative penetrating abilities of gamma radiation and beta particles.

LEARNING OBJECTIVES: By the end of this experiment, the student should be able to demonstrate the following proficiencies:

1. Show that radioactive decay is a first-order kinetic process.
2. Demonstrate the random nature of nuclear disintegrations.
3. Illustrate the fact that radioactivity is a natural phenomenon.
4. Show how to determine the half-life of a radioisotope with a very long half-life.
5. Show how to determine the half-life of a radioisotope with a short half-life.
6. Examine the shielding of radiation by different types of materials.

PRE-LAB: Complete the Pre-Lab Assignment <u>before</u> lab.

DISCUSSION:

Radioactivity is the spontaneous disintegration of unstable atomic nuclei with accompanying emission of radiation. It is known to be a random process at the atomic level, however a bulk (statistical) sample of radioactive material obeys first-order kinetics. Therefore, the rate of radioactive decay at any time *t* is given by:

$$\text{Rate} = -\frac{dN}{dt} = \lambda N \qquad (1)$$

Where λ is the first order rate constant and *N* is the number of radioactive nuclei present at time *t*. (We use λ instead of *k* for rate constant in accord with the notation used by nuclear scientists.) Since radioactive decay is a first order kinetics problem, the half-life for a radioactive nuclide is a constant given by:

$$t_{1/2} = \frac{0.693}{\lambda} \qquad (2)$$

Half-life is the time required for half of a substance to disappear. For a first-order decay process, it is independent of the initial number of particles decaying.

The basic equipment used to measure radioactivity is the Geiger counter. It actually measures the rate, usually in units of counts per minute (cpm). Each "count" is the response of the detector to a single particle (typically α particles, β particles, or γ rays) produced in the decay process. The radiation, which is ionizing, penetrates the detector tube and causes a discharge of a current pulse across the radius of the tube. Thus, each count represents one radioactive nucleus undergoing decay. The counting rate detected by the instrument is called the Activity, A, which is directly proportional to the number of radioactive nuclei:

$$A = \lambda N \qquad (3)$$

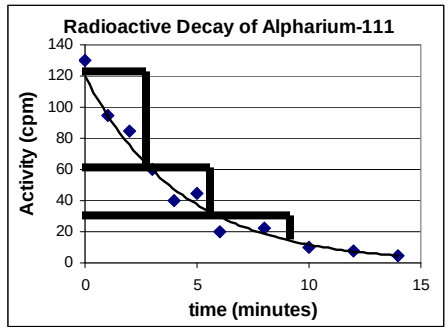
The integrated form of the radioactive decay rate law is also the same as that for first-order chemical kinetics:

$$N = N_0 e^{-\lambda t} \qquad \ln N = -\lambda t + \ln N_0 \qquad (4)$$

where N_0 is the initial number of radioactive nuclei. Since the activity is proportional to the number of radioactive nuclei, these equations are sometimes also written in terms of the activity, $A = A_0e^{-\lambda t}$. In linear form (y = mx + b), the equation becomes

$$ln\ A = -\lambda t + ln\ A_o \qquad (5)$$

where A_0 is the initial activity. Thus, a plot of *ln* A vs. t yields a straight line with a slope that is equal to $-\lambda$. The half-life, $t_{1/2}$, is obtained using Equation 2.



The half-life is most accurately determined from a plot of *ln*(Activity) vs. time. However, it can be estimated from a plot of Activity vs. time, as shown in the figure to the right. The thin solid line represents a smooth curve drawn through the data. The thick solid lines are used to estimate the half-life. (What is the value of the half-life?)

A. Half-Life of a Long-Lived Radioisotope

Samples of the common salt substitute KCl are slightly radioactive due to the presence of ^{40}K, which has an abundance of 0.0118% in naturally occurring potassium. This isotope undergoes radioactive decay primarily by beta emission, with electron capture and positron emission occurring to a smaller extent. The accepted value for the half-life of ^{40}K is 1.28×10^9 years.

For a long-lived isotope such as ^{40}K, the number of radioactive nuclei does not change within any reasonable time of measurement (half-life >> time of measurement). Thus, a direct measurement of the activity for a known sample size yields the decay rate constant, from which the half-life can be determined. (See Equations 2 and 3.)

B. Half-Life of a Short-Lived Radioisotope

Cesium-137 is a radioactive isotope with a half-life of 30.2 years. It undergoes β decay to produce barium-137m, an unstable nuclear "isomer" that further decays to the stable barium-137 nucleus by γ emission:

$$^{137}_{55}Cs \rightarrow {}^{137m}_{56}Ba + {}^{0}_{-1}e \qquad\qquad {}^{137m}_{56}Ba \rightarrow {}^{137}_{56}Ba + \gamma$$

The half-life of ^{137m}Ba is only 2.55 minutes. Because of their different chemical behavior, Cs and Ba can be readily separated and the half-life of the short-lived barium isotope can be followed directly.

An isogenerator (an ion-exchange column) is used in this exercise to generate ^{137}Ba. It is loaded with ^{137}Cs which continually decays to produce the Ba isotope. If a sample of an eluting solution is passed through the column, it will remove only the barium. The eluted solution can then be measured for activity with a Geiger counter at several points over a short (10-15 minutes) time span. A plot of *1n*(Activity) vs. time yields a straight line, thus demonstrating first-order kinetic behavior. (See Equation 5.)

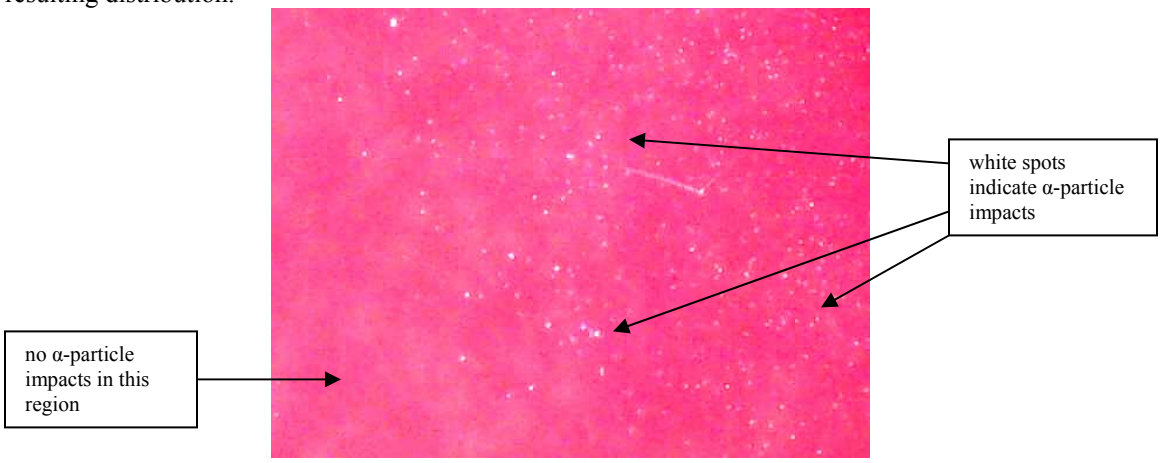
C. Absorption of Radiation

The absorption of radiation depends on the type of radiation (α, β, or γ), the energy of the radiation, and the nature of the absorber. Only β particles and γ rays will be considered in this exercise because the window on the Geiger tube is too thick to allow α particles to enter the tube. In general, γ rays interact with matter in an all-or-nothing way, just like other kinds of photons (e.g., red light). The more matter available per unit area, the greater the attenuation of the beam. The absorbed γ rays disappear and are exchanged for one or two particles (electrons or positrons). β particles, on the other hand, are not “absorbed” by matter but instead are "scattered". As they bounce through the material, they loose their energy a little at a time until they finally come to rest. Because we are using radiation with a very small range in energy, the results for both β and γ absorption will appear similar, but they would not be if a wider range of energy were available.

D. Recreation of the Rutherford Alpha-Particle Scattering Experiment

The famous α-particle scattering experiment performed by Ernest Rutherford in 1910 was fundamental to the discovery of the nuclear nature of the atom. Rutherford passed a beam of α-particles through a very thin gold foil and found that, while the vast majority passed straight through the gold, a small percentage of the particles were deflected, including a few scattered at very large angles. Rutherford was eventually able to explain the result by postulating that most of the mass of the atom resides in a small, extremely dense region called the nucleus, and the rest of the volume of the atom was essentially empty space in which the electrons moved. Most α-particles passed straight through because they did not encounter the minute nucleus. However, the few α-particles that happened to come close to the gold nucleus were repelled by the high positive charge, and thus deviated in path.

Rutherford's system was quite involved, and actually collecting data was extremely difficult. However, we have a demonstration model (available in the hall outside the labs) that permits relatively simple collection of data for α-particles scattered at small angles. It consists of an evacuated plastic chamber holding an α-particle source (^{210}Po), collimator and gold foil at one end, and a disk of α-particle sensitive film at the other. When α-particles hit the red coating on the film they cause damage to the layer. A chemical etching treatment enlarges the damaged areas and removes the color at those points, thus making them visible microscopically. Then one can literally count the white spots that appear at different angles to evaluate the scattering behavior. A sample image is shown below at ~50X magnification. We will analyze a digitally recreated image of one such film, and plot the resulting distribution.



Rutherford's nuclear model and basic electrostatic theory can be used to predict the fraction of α-particles that will be scattered at various angles. The equation is quite complicated, but can be broken down into several terms as

dN/dA = (quantities related to the apparatus) (fundamental electrostatic constants) (properties of α-particle) ($\sin^{-4}(\theta/2)$)

where dN/dA is the number of counts per unit area in a ring of the film at a certain angle, and θ is that scattering angle. (See http://webphysics.davidson.edu/Applets/pqp_preview/contents/pqp_errata/cd_errata_fixes/section4_7.html for further explanation and a simulation.) The dependence of the scattering results on the last term was the key that led to acceptance of the nuclear model. The properties of the α-particle that matter in the calculation are its charge (+2), mass (4.0015 amu) and velocity v. We can use our results to determine the average velocity (in cm/s) of the α-particles scattered by the gold foil. When the full scattering equation is applied to our demonstration apparatus, the result is

$$\frac{dN}{dA} = \frac{4.93x10^{33}\,\frac{cm^2}{s^4}}{v^4}\left(\frac{1}{\sin^4(\theta/2)}\right) \tag{6}$$

Although difficulties in counting and in estimating the total α-particle output of the source may introduce significant error in the calculated result, you should find that the α-particles are ejected from the Po nuclei at very high velocities.

PROCEDURE:

You will be divided into 4 groups and will perform Parts A – D in a round-robin fashion. Do not proceed to another part of the experiment until told to do so by your instructor. Do not touch any radioactive sample or piece of equipment until told to do so by your instructor. You will have approximately 20 minutes to complete each part.

Part A. Half-Life of a Long-Lived Radioisotope

1. Place the thin aluminum plate in the top slot of the white absorber stand. BE CAREFUL NOT TO TOUCH THE BOTTOM FACE OF THE DETECTOR TUBE. Slide a small empty hexagonal weighing boat onto the Al plate, and position it at the center of the stand.

2. Determine the background counting rate as follows. Switch the counter to ON and set the Rate/Continuous switch to CONTINUOUS. The counter will start clicking and the display will show the number of counts. Press and hold down the RESET button; the count will stop. Switch the Rate/Continuous switch to RATE. Release the RESET button. The counter will begin counting for one minute (but the display will not change). After one minute, the counter will update the display with the total counts in that time interval. Record this background count. Repeat the measurement three more times.

3. Accurately weigh, using the top-loading balance, about 2 grams of KCl into the same weighing boat used in #2. The KCl should not be lumpy, but spread out when placing it in the boat. Be careful not to spill any of the KCl. Record the mass of the sample.

4. Position the weighing boat with sample under the detector tube as in step 1. Determine and record the counting rate of (sample + background), using the same procedure as in step 2. Repeat the measurement a total of four times.

5. Remove the sample from the absorber stand and discard the salt in the sink, with running water. Obtain the value of the Detector Efficiency from your Instructor.

Part B. Half-Life of a Short-Lived Radioisotope

1. Do not touch the radioactive sample. Your instructor will prepare it and set it up for you.

2. Familiarize yourself with the Geiger counter. You will likely have to change scale during the course of this exercise. You will probably begin with the X100 scale and change to the X10 scale after the readings fall below 500 (on the X100 scale).

3. Your sample is placed under the Geiger tube by your instructor.

4. Record the activity (in cpm) of the sample in 30 second intervals over a period of 10 minutes, and then for an additional 5 minutes at 1 minute intervals. Take your first reading as time zero ($t = 0$). REMEMBER TO RECORD BOTH THE METER READING AND THE SCALE to obtain the activity value. (Because the readings are not steady, you will probably have to do some averaging by eye. One easy way to even out the readings is to have two members of the group take readings, two serve as recorders, and one serve as the timer. At the end of the 15 minute period, all measurements at a given time can be averaged.)

5. Your instructor will discard the radioactive sample. Do not touch it.

Part C. Absorption of Radiation

1. Place the orange cobalt-60 γ-source in the depression at the bottom of the white plastic Geiger tube stand. (Always place the source with the printed side facing the tube.)

2. Measure and record the activity of the (Co-60 source + background) without absorbers as follows. Switch the counter to ON and set the Rate/Continuous switch to CONTINUOUS. The counter will start clicking and the display will show the number of counts. Press and hold down the RESET button; the count will stop. Switch the Rate/Continuous switch to RATE. Release the RESET button. The counter will begin counting for one minute (but the display will not change). After one minute, the counter will update the display with the total counts in that time interval.

3. Locate the thin Al foil that is packaged in a cardboard slide mount. **(THESE FOILS ARE QUITE FRAGILE; DO NOT TOUCH THE FOIL ITSELF, BUT HANDLE ONLY BY THE CARDBOARD MOUNT!)** Place it in the slot closest to the Geiger tube. Set the Rate/Continuous switch to CONTINUOUS. The counter will start clicking and the display will show the number of counts. Press and hold down the RESET button; the count will stop. Switch the Rate/Continuous switch to RATE. Release the RESET button. The counter will begin counting for one minute (but the display will not change). After one minute, the counter will update the display with the total counts in that time interval. Record the activity measured with the thin Al foil absorber.

4. Remove the Al foil and replace it with one thick Al plate. Repeat the measurement and record the activity with the thick Al plate absorber.

5. Remove the Al plate and replace it with a thick lead sheet. DO NOT BEND THE Pb SHEET! Repeat the measurement. Add a second Pb sheet (in another slot) and repeat the measurement.

6. Remove the Pb sheets and replace them with one plastic plate. Repeat the measurement.

7. Remove all absorbers and replace the orange cobalt-60 γ-source with the green strontium-90 β-source.

8. Repeat steps 2 through 6, recording the original source activity, and the activities with the various absorbers as before.

9. Remove all absorbers. Move the sources at least two feet away from the Geiger tube. Repeat the measurement once to obtain a background count.

Part D. Recreation of the Rutherford Alpha-Particle Scattering Experiment

At some time during this segment, go into the hallway and examine the demonstration Rutherford α-particle scattering device. Sketch the apparatus and identify the Po-210 source, the Au foil, and the target film. If available, use the microscope to examine a sample piece of film for evidence of α-particle impacts.

1. Examine the enlarged copy of an exposed and developed film from the Rutherford device. The target is divided into 8 segments (A-H), and each segment divided into 10 concentric rings separated by one degree (numbered 2-11). The data required is the number of α-particle impacts in each ring.

2. Each midshipman in the group should choose ONE segment, and count the number of white spots (α-particle impacts) in each ring of his/her segment. Skip the heavily impacted innermost circle, and begin counting between rings 2 and 3, 3 and 4, etc. Most spots are circular, but occasionally ovals will appear; just simply count them the same. (The ovals result from the chemical treatment of particle tracks that entered the film at a shallow angle.)

Name _____ Section _____

Partners _____ Date _____

DATA SECTION
Experiment 13N

Part A. Half-Life of a Long-Lived Radioisotope

Mass of KCl sample: _____ grams

Background Activity (counts per minute)	Total Activity (counts per minute)
_____	_____
_____	_____
_____	_____
_____	_____
average:_____	**average:**_____

Detector Efficiency _____ (see instructor)

Part B. Half-Life of a Short-Lived Radioisotope

Time (minutes)	Activity (cpm)	Time (minutes)	Activity (cpm)
_____	_____	_____	_____
_____	_____	_____	_____
_____	_____	_____	_____
_____	_____	_____	_____
_____	_____	_____	_____
_____	_____	_____	_____
_____	_____	_____	_____
_____	_____	_____	_____
_____	_____	_____	_____
_____	_____	_____	_____
_____	_____	_____	_____
_____	_____	_____	_____
_____	_____	_____	_____

Part C. Absorption of Radiation

Cobalt-60 Gamma Source		Strontium-90 Beta Source	
Absorber	Activity (cpm)	Absorber	Activity (cpm)
None	_____	None	_____
Al foil	_____	Al foil	_____
Al plate	_____	Al plate	_____
1 Pb sheet	_____	1 Pb sheet	_____
2 Pb sheets	_____	2 Pb sheets	_____
plastic plate	_____	plastic plate	_____

Background _____ cpm

Part D. Recreation of the Rutherford Alpha-Particle Scattering Experiment

Enter the required data in the table below.

Ring Range (deg)	Segment _____	Segment _____	Segment _____	Segment _____	Segment _____
2-3					
3-4					
4-5					
5-6					
6-7					
7-8					
8-9					
9-10					
10-11					

Sketch the Rutherford device. Identify the α-particle source, gold foil, and target film in your sketch.

Name _____ Section _____

Partners _____ Date _____

DATA TREATMENT / IN-LAB WORKSHEET
Experiment 13N

Part A. Half-Life of a Long-Lived Radioisotope

1. Average your four measurements of the background activity, and average the four measurements of the (sample + background) activity. Calculate the apparent activity of the KCl sample alone in units of counts/min (cpm).

apparent activity of KCl sample: _____ cpm

2. Calculate the true activity of the KCl sample, based on the apparent activity and the detector efficiency factor obtained from your Instructor.

true activity of KCl sample: _____ cpm

3. From the actual mass of the KCl sample, calculate the number of radioactive ^{40}K nuclei in the KCl sample. The known isotopic abundance of potassium-40 is 0.0118%.

number of ^{40}K nuclei: _____

4. From the true activity and known number of ^{40}K atoms, calculate the half-life of ^{40}K in units of years.

$t_{1/2}$ of ^{40}K: _____ years

5. The accepted half-life of ^{40}K is 1.28×10^9 years. Calculate the percent error of your measurement.

percent error: _____

Part B. Half-Life of a Short-Lived Radioisotope

1. Create a spreadsheet that contains the following columns:

   time (min) activity (cpm) *ln* Activity

   Input your time and activity data, and use a formula to compute *ln* Activity. Make two graphs:

   (1) Plot Activity vs. time.
   (2) Plot *ln* Activity vs. time and perform a linear regression. Your plot should be properly labeled, and the linear regression equation and R^2 should be shown on the graph.

   Slope of line: _____

   y-intercept of line: _____ R^2: _____

   Submit your spreadsheet and the two graphs with your lab report.

2. From your linear regression equation, calculate the half-life of ^{137}Ba in units of minutes.

   $t_{1/2}$ of ^{137}Ba: _____ min

3. The accepted half-life of ^{137}Ba is 2.55 min. Calculate the percent error of your measurement.

   percent error: _____

4. On your Activity vs. time plot, <u>draw a smooth line</u> through the data, then indicate, on the plot, the first 3 half-lives of Ba-137m. List the times of these successive half-lives:

   first half-life: _____ min

   second half-life: _____ min

   third half-life: _____ min

   average half-life: _____ min

5. The half-lives should be constant (all take the same amount of time), another feature characteristic <u>only</u> of first-order kinetic behavior. How does your average half-life, determined here, compare to that obtained from the first-order rate law (item 2)?

   percent difference: _____

Part C. Absorption of Radiation

Perform the following calculations and write the results in the table below, or in a similar Excel spreadsheet.

1. A simple way to quantify the absorbers is with their "area density", which is the mass absorber per unit area. The area densities for the various absorber components are:

   thin Al foil: 21.5 mg/cm^2 thick Al plate: 40.9 mg/cm^2 single Pb sheet: 188.3 mg/cm^2

   Calculate the total area density employed for each of the absorption measurements obtained. This is done by multiplying the appropriate value above by the number of plates/sheets used.

2. Determine values of the Corrected Activity by subtracting the Background from the Measured Activity.

3. The Corrected Activity for the Co-60 gamma source or Sr-90 beta source without absorbers represents 100% penetration. Calculate the percent penetration for each of the other Corrected Activities.

4. Plot the Percent Penetration vs. the Absorber Area Density. Show both the beta and gamma results on the same graph. Use different marker styles for each plot (gamma and beta) and identify them in the legend. Your data points should be connected with lines. Submit the spreadsheet and graph with your lab report.

5. Based on your plot, estimate the area density value for the plastic plate.

Absorption of Radiation Calculations

			Cobalt-60 Gamma Source				Strontium-90 Beta Source		
Absorber	**Total Area Density (mg/cm^2)**		**Measured Activity (cpm)**	**Corrected Activity (cpm)**	**Penetration (%)**		**Measured Activity (cpm)**	**Corrected Activity (cpm)**	**Penetration (%)**
no absorber									
thin Al foil									
thick Al plate									
single Pb sheet									
two Pb sheets									
plastic plate									

Part D. Recreation of the Rutherford Alpha-Particle Scattering Experiment

1. Enter your data for the number of counts in each ring, in each measured segment, in the table below, or a similar Excel spreadsheet table.

		Number of Counts in Each Ring and Segment								
Ring Range	**Angle (deg)**	**Segment _____**	**Segment _____**	**Segment _____**	**Segment _____**	**Segment _____**	**Average (in segment)**	**Total Counts (in ring)**	**Ring Area (cm^2)**	**Counts/ Area (cm^{-2})**
2-3	**2.5**								**0.257**	
3-4	**3.5**								**0.360**	
4-5	**4.5**								**0.463**	
5-6	**5.5**								**0.566**	
6-7	**6.5**								**0.669**	
7-8	**7.5**								**0.772**	
8-9	**8.5**								**0.875**	
9-10	**9.5**								**0.978**	
10-11	**10.5**								**1.081**	

2. Average the measured counts in each ring and enter the values in the table. Multiply the Average counts/segment in each ring by 8 to get the Total Counts in each ring and enter those values. Areas of the rings are listed in the table; use those values to determine the total number of counts per unit area for each ring.

3. Create a plot of the Counts/Area vs. the scattering angle. This describes the distribution of α-particles scattered by the gold foil.

4. Your value of Counts/Area is the experimental measurement of dN/dA, which appears in Equation (6) in the Discussion section. Use that equation, and your values of Counts/Area and Angle to determine the velocity v (in cm/s) of alpha particles for each of the rings measured. You should obtain approximately the same value for each. (NOTE: if performing this calculation in Excel, you must use angles expressed in radians when you use the SIN function. Note also that the equation uses ½ the angle, not the scattering angle itself, in the sine term.)

5. Average your calculated values for the velocity of the alpha particles. Compare the average to the accepted value for alpha particles emitted by the Po-210 nucleus, which is 1.60×10^9 cm/s. Calculate the percent error. How many miles would these particles travel in one second?

QUESTIONS
Experiment 13N

1. Write balanced nuclear equations describing the decay of potassium-40 by the three modes of decay mentioned in Part A on page E13N-2. Are the product nuclei stable?

2. In determining the half-life of barium-137m, it was not necessary to subtract out the background. Why not?

3. You used a strontium-90 beta source in Part C. Write the balanced nuclear reaction showing this β-decay.

4. In many instances in these experiments, you might have tried to make identical measurements but obtained different values of the Activity. How can that be? (HINT- it is probably NOT operator error!)

5. Complete the "Nuclear Checkerboard" exercise. Your instructor will provide the materials if he or she wants you to answer this question.

Name _____ Section _____
Date _____

PRE-LAB QUESTIONS
Experiment 13N

1. The nuclear disaster at Chernobyl – review the following website and answer the questions below.

http://en.wikipedia.org/wiki/Chernobyl_accident (or search for other sites)

Note that the Chernobyl plant is no longer operational but is open to tourists!

i. When did the Chernobyl nuclear disaster occur?

a. 1986 b. 1990 c. 1909 d. 1968 e. 2006

ii. What caused the disaster? Select all that apply.

a. disregard of safety procedures
b. flawed reactor design
c. lack of any control rods
d. overthrow of the government
e. terrorist attack on the plant
f. operator error

iii. Due to radioactive fallout, approximately how many people had to be relocated or moved from the area?

a. ~ 100 b. ~ 1000 c. ~ 10,000 d. ~ 100,000 e. ~1,000,000

iv. About how many people were killed or suffered long term serious health problems caused by radiation exposure from the Chernobyl accident?

a. none b. ~ 50 c. ~ 1000 d. ~ 10,000 e. ~ 100,000

2a. Use the table on p. 1013 of the Chang text to estimate your total annual exposure to radiation. For your information, Annapolis is a little above sea level (<1000 ft elevation), Bancroft Hall is made of stone, and the nearest nuclear power plant is the Calvert Cliffs plant in Lusby, MD, about 40 mi. away. What is your total annual estimated exposure, in mrem?

_____ mrem

b. How does this compare to operators and firefighters present at the time of the Chernobyl accident, who received doses between 80 and 1600 rem in a relatively short period of time?

3. Assume that you spend only 20 minutes doing Part C of the experiment, and that you are exposed to β- and γ-radiation at a rate of 1.0×10^{-3} rem/hr (total). What will be your exposure in mrem? To how many rads does this correspond?

_____ mrem

_____ rad

4. Superman was claimed to be "faster than a speeding bullet". How fast is that? (You pick the weapon and ammo.) Compare that to the speed of an α-particle emitted by a Po nucleus in the Rutherford scattering experiment, which was 1.6×10^{9} cm/sec?