Experiment 13N

12/18/2018

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; 3 Daedalon counters with probes; 3 white Geiger probe/absorber holders; 1 thin Al foil (#5); 2 Al plates; 1 plastic absorber; 2 Pb sheets; 12 HDPE absorbers; 4 Petri dishes; disposable gloves (for instructor).

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, but the bulk (statistical) behavior of a sample of radioactive material is readily seen to obey first-order kinetics. The first-order differential rate law for radioactive species has the same form as the equation applied to chemical kinetic processes, but it is usually expressed in terms of the number of radioactive nuclei, N, rather than the concentration:

$$\text{Rate} = -\frac{dN}{dt} = k\,N \tag{1}$$

where dN/dt is the change in the number of radioactive nuclei with respect to time, t, and k is the rate constant. As is characteristic of first-order decay processes, the rate constant is related to the half-life, $t_{1/2}$, by the equation

$$t_{1/2} = \frac{0.693}{k} \tag{2}$$

The 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:

$$A = k\,N \tag{3}$$

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

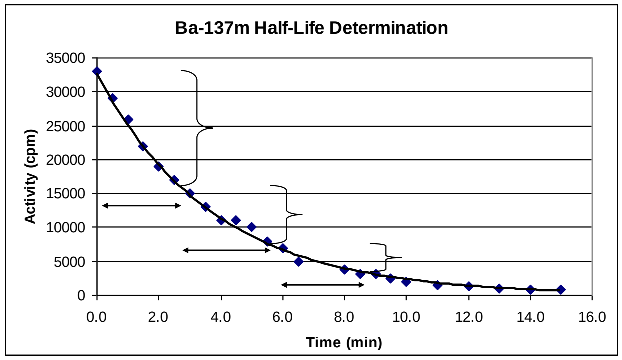
$$N = N_0 e^{-kt} \qquad\qquad \ln N = -k\,t + \ln N_0 \tag{4}$$

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, $A = A_0e^{-kt}$. In linear form (y = mx + b), the equation becomes

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

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 –k. 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 brackets indicate 50% decreases in activity; each double-headed arrow is one half-life. Note that each half-life has the *same* duration.



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:

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

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 lose 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. Radiation Shielding: Fractional-Value Thickness Determination for HDPE Shielding

In Part C of the Radioactivity lab, you determined the relative shielding power of aluminum, lead and polycarbonate plastic, for both beta particles and gamma rays. In this part we will evaluate widely-used quantitative measures of shielding ability, the "half-value thickness (HVT)" and the "tenth-value thickness (TVT)". The half-value thickness is defined as the thickness of shielding material required to reduce the radiation level to one-half its initial value. The TVT is similarly defined as the amount of shielding required to reduce activity levels by a factor of ten. These values can be used to calculate the thickness required to achieve a desired reduction in worker exposure to radiation. For example,

$$\text{shielded dose} = \text{source dose x } 10^{-\text{thickness/TVT}} \qquad (6)$$

The thickness of shielding required for protection depends on the nature of the radiation (α, β or γ), and the highly penetrating gamma rays are of greatest concern. Shielding values also depend on the energy of the radiation, so the HVT or TVT will vary for different radionuclides. Some TVT values of common nuclear shielding materials for different energy gamma rays are given in the table below. The half-value thickness for any material is generally about one third of the tenth-value thickness for that material.

	LEAD	STEEL	CONCRETE	WATER
Tenth Value, 1 MeV γ	1.5 in	3.0 in	12 in	24 in
Tenth Value, 6 MeV γ	2.0 in	4.0 in	24 in	48 in
"RP-4, Radiation Protection" in Health Physics Course, www.nukeworker.com, accessed 29 March 2012. 1 MeV = 10^6 eV. 1 eV = 1.602×10^{-19} J				

Cobalt-60, a common gamma source, emits gamma rays at energies of 1.17 and 1.33 MeV. Thus, a substantial amount of lead would be required to quantitatively measure shielding effects for this isotope. The same principle can be observed with the less-penetrating beta particles emitted by strontium-90 by employing a less dense material – high density polyethylene (HDPE). Using thin (0.50 mm) strips of HDPE cut from plastic milk bottles, we will determine the TVT and HVT values of that absorber for 0.55 MeV betas emitted by ^{90}Sr.

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. Perform 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. The barium isotope is highly radioactive. Your instructor will prepare and operate the isogenerator, and display the Geiger counter output on the projector screen. Data will be taken simultaneously by the whole class.

2. Your instructor will have to change the Geiger counter 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. 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. Your instructor may assign one student as the timer to call out the intervals, so that others can keep watching the needle and mentally average the readings near the designated time.

4. 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: Fractional Value Thickness

1. Measure and record the background activity (without source or absorbers) as follows. Make sure the sources are at some distance from the detector. 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 that value.

2. Place the green strontium-90 β-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.)

3. Measure and record the activity of the (Sr-90 source + background) without absorbers as was done for the background. Count for one minute and record the result. While the system is counting, stack the HDPE strips in bundles of 2 strips.

4. Place one bundle of two HDPE absorber strips directly on the source. Count for one minute and record the results.

5. Repeat step 4, adding bundles of additional strips to the pile, counting and recording for one minute after each bundle is placed. Continue until 6 bundles (12 strips total) have been added. As the pile gets taller, be sure the strips remain centered over the source for best shielding ability.

   When finish, remove all HDPE strips and turn off the detector.

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)
0			

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: Fractional Value Thickness – HDPE Data

Background _____________ cpm

No. sheets	Activity (cpm)
0	_____________
2	_____________
4	_____________
6	_____________
8	_____________
10	_____________

Name ____ Section ______________________

Partners ______________________________________ Date ________________________

DATA TREATMENT
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. *Activity is on the y-axis.*
   (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: ____________________ (include units)

   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 ^{137m}Ba in units of minutes.

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

3. The accepted half-life of ^{137m}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 barium-137m. List the durations 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. By what percentage does the half-life determined here differ from that obtained from the first-order rate law (item 2)?

   percent difference: _______________

Part C. Absorption of Radiation

Perform the following calculations in a spreadsheet, using the template below. Note that some of the column headings are long. To fit these headings into a column of reasonable width, wrap the text by the following steps: Go to the Home tab, go into the Alignment group, and click Wrap text.

1. A simple way to quantify the absorbers is with their "area density", which is the mass absorber per unit area. Calculate the total area density employed for each of the absorption measurements obtained. This is done by multiplying the area density for the absorber by the number of plates/sheets used. The area densities for the various absorber components are:

absorber	area density (mg/cm^2)
thin aluminum foil	21.5
thick aluminum plate	40.9
single lead sheet	188.3

   Note that a value is not given for the plastic plate; this value will be estimated from your plots, and entered into the spreadsheet.

2. Input your Measured Background and Measured Activities. Then, calculate 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 (% penetration is on the y-axis). 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.

5. Based on your plot, estimate the area density value for the plastic plate, in units of mg/cm^2. Enter this value in the appropriate cell.

6. Submit the spreadsheet and graph with your lab report.

Template for Spreadsheet

		Cobalt-60 Gamma Source			**Strontium-90 Beta Source**		
Absorber	**Total Area Density (mg/cm^2)**	**Measured Activity (cpm)**	**Corrected Activity (cpm)**	**Percent Penetration**	**Measured Activity (cpm)**	**Corrected Activity (cpm)**	**Percent Penetration**
no absorber	0			100			100
thin Al foil							
thick Al plate							
single Pb sheet							
two Pb sheets							
plastic plate							

Part D: Fractional Value Thickness

1. Set up an Excel spreadsheet containing columns for Number of Absorber Sheets, Measured Activity, and Corrected Activity. Enter your data. Use the measured background value to correct all of your readings.

2. Make a plot of Corrected Activity vs. the No. of Absorber Sheets. (Corrected Activity is on the y-axis).

3. Fit the data to an exponential trendline, which has the form

$$y = a\,e^{-bx} \quad (7)$$
$$\text{Corrected Activity} = a\,e^{-b(\#\ \text{absorbers})} \quad (8)$$

   where a and b are the fitted parameters. Display the trendline equation and the R^2 value on the graph. You should get at least 3 significant figures for "a" and "b". If not, right-click on the trendline equation, click "format trendline label", and change the Number category to another category that will give at least 3 significant figures.

   trendline equation ____ R^2 ___________________

   Submit your spreadsheet and graph with your lab report.

4. From your data, determine the corrected activities which correspond to the initial value, one-half the initial value, and one-tenth the initial value. Enter these values into the table below. (*Because the exponential trendline may not adequately fit the data at small numbers of absorber sheets, the initial corrected activity is taken from the data, not the fitted line.*)

5. Using your trendline equation, calculate the number of absorber sheets (x) that correspond to the 1/2 and 1/10 values of corrected activities. Show your work and enter your values in the table below. (Note that these calculated values correspond to the half-value and the tenth-value shielding thicknesses (HVT and TVT, respectively).

	Corrected Activity (cpm)	**Number of Absorber Sheets**
initial (no absorbers)		0
1/2 of initial		
1/10 of initial		

6. From the known thickness of the HDPE sheets (0.50 mm), calculate the HVT in units of mm (show work).

7. From the known thickness of the HDPE sheets (0.50 mm), calculate the TVT in units of mm (show work).

Name ____ Section ______________________

Partners ______________________________________ Date ________________________

POST-LAB 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 Parts C and D. Write the balanced nuclear equation 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. During the Fukushima nuclear disaster, a dose rate of 40,000 mrem/hr of 1 MeV gamma radiation was reported at a leak site. What thickness of lead shielding would be required to reduce this level to less than 1 mrem per 6-hour shift? Show your work. The TVT value for lead is in the table in the Discussion section. See also equation 6.

Name ____ Section ________________

Date __________________

PRE-LAB QUESTIONS
Experiment 13N

1. The nuclear disaster at Chernobyl – review the following websites and answer the questions below.
   http://en.wikipedia.org/wiki/Chernobyl_accident
   http://www.nrc.gov/reading-rm/doc-collections/fact-sheets/chernobyl-bg.html (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 up to the year 2000?

   a. ~ 300 b. ~ 3000 c. ~ 30,000 d. ~ 300,000 e. ~3,000,000

   iv. About how many deaths were directly attributable to radiation exposure from the Chernobyl accident?

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

   v. What type of explosion(s) was/were thought to destroy the reactor? Select all that apply.

   a nuclear b. steam c. chemical d. none

2. Consult the Nuclear Regulatory Commission website http://www.nrc.gov/about-nrc/radiation/around-us/calculator.html to answer the questions below.

   a. 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 miles away. There are several coal-fired power plants near Baltimore, ~ 30 miles 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. According to the NRC website http://www.nrc.gov/about-nrc/radiation/around-us/doses-daily-lives.html, eating 1 kg of red meat exposes us to 3000 pCi of ^{40}K radiation. What is the ^{40}K activity, in counts per minute, of an 8-oz rare steak? (1 Ci = 3.7×10^{10} decays (counts) per second.)