7.5: Nuclear Physics (Activities)

A radioactive sample undergoes three different types of radioactive decays and emits three different types of particles.

I. The particles are emitted into a region of space with a uniform magnetic field directed out of the page and follow the paths indicated. None of the particles bend either into or out of the screen. For each path, identify the radioactive decay (▯▯▯▯▯▯▯▯▯▯▯▯) or state that the type of decay cannot be determined based on the information provided. Ignore the neutrinos (and antineutrinos) emitted in beta decay.

a.

b.

c.

II. The particles are directed toward a series of barriers and follow the paths indicated. For each path, identify the most likely radioactive decay (▯▯▯▯▯▯▯▯▯▯▯▯) or state that the type of decay cannot be determined based on the information provided. Ignore the neutrinos (and antineutrinos) emitted in beta decay.

d.

e.

f.

The activity of six different radioactive samples is tracked over a 10 year period and graphed below.

a. Rank these samples on the basis of their half-life.

Largest 1. _____ 2. _____ 3. _____ 4. _____ 5. _____ 6. _____ Smallest

_____ The ranking cannot be determined based on the information provided.

Explain the reason for your ranking:

b. Rank these samples on the basis of their decay constant.

Largest 1. _____ 2. _____ 3. _____ 4. _____ 5. _____ 6. _____ Smallest

_____ The ranking cannot be determined based on the information provided.

Explain the reason for your ranking:

Six radioactive samples, with different half-lives and initial activities, are listed below.

Half-life (min) Activity (mCi)
A 1.0 160
B 6.0 80
C 4.0 80
D 2.0 40
E 1.0 320
F 8.0 40

a. Rank these samples on the basis of their activity after 4.0 minutes.

Largest 1. _____ 2. _____ 3. _____ 4. _____ 5. _____ 6. _____ Smallest

_____ The ranking cannot be determined based on the information provided.

Explain the reason for your ranking:

b. Rank these samples on the basis of their activity after 8.0 minutes.

Largest 1. _____ 2. _____ 3. _____ 4. _____ 5. _____ 6. _____ Smallest

_____ The ranking cannot be determined based on the information provided.

Explain the reason for your ranking:

The graphic below illustrates the valley of stability, the collection of stable, metastable, and unstable nuclei in terms of atomic number and neutron number.

a. Examine the number of stable nuclei at odd values of N vs. even values of N. Does one value lead to consistently more stable nuclei? If so, explain why this occurs.

b. Examine the number of stable nuclei at odd values of Z vs. even values of Z. Does one value lead to consistently more stable nuclei? If so, explain why this occurs.

c. In addition to the simple relationships above, certain values of N have an inordinate number of stable nuclei, for example 5 or more. What are these magic numbers of neutrons?

d. Are the same numbers magic for protons? If so, explain why this happens. (Hint: Consider what you know about the allowed occupancy of different atomic energy levels.)

The graphic below illustrates the valley of stability, the collection of stable, metastable, and unstable nuclei in terms of atomic number and neutron number.

a. Examine the nucleus indicted above, with Z = 21 and N = 19. Based only on the graphic, how do you think this nucleus decays? What nucleus (or nuclei) does it decay into?

b. Examine the nucleus indicted above, with Z = 9 and N = 13. Based only on the graphic, how do you think this nucleus decays? What nucleus (or nuclei) does it decay into?

c. Examine the nucleus indicted above, with Z = 35 and N = 42. Based only on the graphic, how do you think this nucleus decays? What nucleus (or nuclei) does it decay into?

d. Examine the nucleus indicted above, with Z = 19 and N = 21. Based only on the graphic, how do you think this nucleus decays? What nucleus (or nuclei) does it decay into?

I. Why are beta particles absorbed by a sheet of metal while gamma particles require several inches of lead for absorption?

Barbie: Gamma particles move at the speed of light. The faster something moves, the more difficult it is to stop.

Kathleen: Gamma particles are smaller than betas. That's what makes them more difficult to stop.

Kevin: Beta particles are charged, so they are easily stopped by electrical conductors.

Which, if any, of the students are correct? For each incorrect response, provide a short explanation why it is incorrect. If no one is correct, provide a correct answer below.

II. Why is it so important not to eat or drink in the vicinity of radioactive materials?

Robert: You may accidentally ingest some of the radioactive materials before they have decayed. This could be dangerous.

Paul: If your food or drink gets "hit" by the radioactive particles it could become harmful to consume.

Betty: You may accidentally ingest some of the radioactive materials after they have decayed. This could be dangerous.

Which, if any, of the students are correct? For each incorrect response, provide a short explanation why it is incorrect. If no one is correct, provide a correct answer below.

Complete the following hypothetical radioactive chain with the correct decay process on each line and the correct nucleus in each box.

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I. Why must 235U be separated from 238U when constructing a fission bomb?

Otto: Any 238U in the bomb material will absorb neutrons rather than be fissioned by them. Since the neutrons needed for the chain reaction are produced by fission, any 238U in the bomb would cause the chain reaction to "fizzle".

Fritz: 238U does not have as much nuclear energy as 235U. Thus, the bomb would be much less powerful.

Lise: Any 235U in the bomb material will absorb neutrons rather than be fissioned by them. Since the neutrons needed for the chain reaction are produced by fission, any 235U in the bomb would cause the chain reaction to “fizzle”.

Which, if any, of the students are correct? For each incorrect response, provide a short explanation why it is incorrect. If no one is correct, provide a correct answer below.

II. Why can’t a fission bomb be constructed from less than the critical mass of fissionable material?

Albert: If you have less than the critical mass of fissionable material, you run the risk of the bomb spontaneously detonating (which is obviously something you’d like to avoid).

Edward: If you have less than the critical mass of fissionable material, the chain reaction that causes the bomb to denote will not occur.

Emile: If you have less than the critical mass of fissionable material, the bomb will not be powerful enough to destroy anything.

Which, if any, of the students are correct? For each incorrect response, provide a short explanation why it is incorrect. If no one is correct, provide a correct answer below.

I. What is the source of the energy released in a fission bomb?

Michala: The energy is initially stored in the chemical bonds of the uranium. As the chemical reaction unfolds, and uranium changes into other materials, this energy is released.

Fiona: A fission bomb requires a chain reaction mediated by neutrons. The kinetic energy, or energy of motion, of the neutrons provides the energy released by the bomb.

Kip: The energy released by the bomb is due to a very small decrease in the mass of the bomb materials as they undergo fission. This small decrease is mass-energy is equivalent to a huge release of other forms of energy.

Which, if any, of the students are correct? For each incorrect response, provide a short explanation why it is incorrect. If no one is correct, provide a correct answer below.

II. What is the primary difference between a fission and fusion reaction?

Ian: Fission reactions occur on earth and fusion reactions occur in the sun.

Tom: Fusion reactions release more energy than fission reactions.

Matt: Fusion reactions release no harmful by-products while fission reactions release various highly dangerous by-products.

Which, if any, of the students are correct? For each incorrect response, provide a short explanation why it is incorrect. If no one is correct, provide a correct answer below.

Find the total binding energy for 4He, 3He, and 3H.
a. Based on these results, how much energy is needed to remove a single neutron from 4He?
b. Based on these results, how much energy is needed to remove a single proton from 4He?
c. Carefully explain why the proton is easier to remove than the neutron.

Mathematical Analysis

Find the total binding energy for 56Fe, 55Fe, and 55Mn.
a. Based on these results, how much energy is needed to remove a single neutron from 56Fe?
b. Based on these results, how much energy is needed to remove a single proton from 56Fe?
c. Carefully explain why the proton is easier to remove than the neutron.

Mathematical Analysis

Find the binding energy per nucleon for 15O and 15N. Based on these results, which of these two isobars do you expect to be more plentiful in nature?

Mathematical Analysis

Find the binding energy per nucleon for 13C and 13N. Based on these results, which of these two isobars do you expect to be more plentiful in nature?

Mathematical Analysis

28Al has a half-life of 2.24 minutes.
a. What is ?
b. What percentage of a given sample will remain after 1.0 hr?

Mathematical Analysis

Tritium, 3H, has a half-life of 12.3 yrs.
a. What is ?
b. What percentage of a given sample will remain after 50 yr?

Mathematical Analysis

A radioactive sample decays at a rate of 500 per second. After 1 hr, the rate has decreased to 225 per second.
a. What is the half-life of the sample?
b. What will be the decay rate after 2 hr?
c. What percentage of the sample will remain after 10 hr?

Mathematical Analysis

A 2.00 mCi sample of 131I has a half-life of 8.04 days.
a. What will be the decay rate after 30 days?
b. What percentage of the sample will remain after 30 days?

Mathematical Analysis

Natural potassium contains 0.012 percent 40K, which has a half-life of 1.3 x 109 yrs.
a. What is the activity of 1.0 kg of potassium?
b. What was the percent 40K in natural potassium 4.4 x 109 yrs ago?

Mathematical Analysis

Humans have about 2.5 g of potassium per kilogram of body mass. The average 150 g banana contains about 0.5 g potassium. Natural potassium contains 0.012 percent 40K, which has a half-life of 1.3 x 109 yrs.
a. What is the activity of a 70 kg human due to 40K decay?
b. If he eats a banana, by what percentage does his activity increase? (This increase in activity lasts for about 3 hrs until his kidneys eliminate the excess potassium.)

Mathematical Analysis

A piece of wood from a recently cut tree shows 13 14C decays per minute. An old axe handle of the same mass shows 3 decays per minute. How old is the axe handle? The half-life of 14C is 5730 yrs.

Mathematical Analysis

A sample of charcoal from an ancient fire pit has a mass of 0.36 g and is essentially pure carbon. The measured activity of the sample is 0.01 Bq. How old is the sample? In the environment, about one carbon atom in 7.7 x 1011 is 14C. The half-life of 14C is 5730 yrs.

Mathematical Analysis

A sample of leather from a tomb is burned to obtain 0.12 g of carbon. The measured activity of the sample is 0.012 Bq. How old is the sample? In the environment, about one carbon atom in 7.7 x 1011 is 14C. The half-life of 14C is 5730 yrs.

Mathematical Analysis

In uranium-lead dating, two independent age estimates for the same substance can be made by comparing the ratio of specific isotopes of lead and uranium in a sample. 238U decays to 206Pb through a 14-step process that has an overall half-life of 4.47 x 109 yr. 235U decays to 207Pb through an 11-step process that has an overall half-life of 704 x 106 yr. Aside from supernovae explosions, these isotopes of lead are only formed by these processes. Thus, the ratio of lead to uranium in a sample can be used to determine the age of the sample. Consider a sample of zircon that contains 8 206Pb atoms for every 100 238U atoms and 62 207Pb atoms for every 100 235U atoms.
a. What is the age of the sample based on the amount of 206Pb present?
b. What is the age of the sample based on the amount of 207Pb present?
c. How would you report the age of this sample?

Mathematical Analysis

230Th undergoes alpha decay with a half-life of 75,400 years. Consider a 1 kg sample of pure 230Th.
a. What is the initial power output (in Watts) of this sample?
b. How long will it take for the activity to drop to 1 decay/s?
c. What is the kinetic energy of the emitted alpha particle?

Mathematical Analysis

239Pu undergoes alpha decay with a half-life of 24,100 years. Consider a 1 g sample of pure 239Pu.
a. What is the initial power output (in Watts) of this sample?
b. How long will it take for the activity to drop to 1 decay/s?
c. What is the kinetic energy of the emitted alpha particle?

Mathematical Analysis

211Rn undergoes alpha decay with a half-life of 14.6 h. Consider a 0.01 mol sample of pure 211Rn.
a. What is the initial activity of this sample?
b. How long will it take for the power output of this sample to drop to 1% of its initial value?
c. What is the kinetic energy of the emitted alpha particle?

Mathematical Analysis

The vital ingredient of household smoke detectors is a very small quantity (~35 kBq) of americium-241 (241Am). (This element was discovered in 1945 during the Manhattan Project. The first sample of americium was produced by bombarding plutonium with neutrons in a nuclear reactor at the University of Chicago. As if you cared.) 241Am undergoes alpha decay with a half-life of 432 years.
a. How long will it take for the activity to drop to 1 decay/s (1 Bq)?
b. What is the initial power output (in Watts) of this sample?
c. How many grams of 241Am are in a typical smoke detector?

Mathematical Analysis

24Na is unstable.
a. How can it decay? Calculate the Q value for each decay.
b. Which decay dominates?

Mathematical Analysis

28Al is unstable.
a. How can it decay? Calculate the Q value for each decay.
b. Which decay dominates?

Mathematical Analysis

18F is unstable.
a. How can it decay? Calculate the Q value for each decay.
b. Which decay dominates?

Mathematical Analysis

32P is unstable.
a. How can it decay? Calculate the Q value for each decay.
b. Which decay dominates?

Mathematical Analysis

36Cl is unstable.
a. How can it decay? Calculate the Q value for each decay.
b. Which decay dominates?

Mathematical Analysis

58Co is unstable.
a. How can it decay? Calculate the Q value for each decay.
b. Which decay dominates?

Mathematical Analysis

The atomic masses of 3918Ar, 3919K, and 3920Ca are 38.964315u, 38.963999u, and 38.970718u.
a. Which one(s) are stable?
b. How will each unstable nuclei decay?

Mathematical Analysis

The atomic masses of 8134Se, 8135Br, 8136Kr, and 8137Rb are 80.917990u, 80.916289u, 80.916589u, and 80.918990u.
a. Which one(s) are stable?
b. How will each unstable nuclei decay?

Mathematical Analysis

40K undergoes all three beta decays: 89% of the time beta-minus, 11% of the time electron capture, and very rarely beta-plus.
a. Find the Q value for each decay.
b. Find a weighted average Q value for 40K decay.

Humans have about 2.5 g of potassium per kilogram of body mass. The average 150 g banana contains about 0.5 g potassium. Natural potassium contains 0.012 percent 40K, which has a half-life of 1.3 x 109 yrs.
c. What is the average power output of an 80 kg man due to 40K decay?
d. How many bananas would it take to light a 60 W bulb? Assume all of the 40K power output is somehow channeled into the light bulb.

Mathematical Analysis

In positron-emission tomography (PET scanning), a radioactive isotope that emits positrons is introduced into the body. Upon decay, the emitted positron immediately annihilates with a nearby electron releasing a pair of oppositely directed gamma rays. Detecting these gamma rays allows a precise determination of the location of the decay. For brain scans, a common tracer is glucose incorporating a small amount (approximately 1.0 x 10-9 g) of 11C, whose half-life is 20 min. (Glucose can cross the blood-brain barrier and enter the brain.)
a. Find the Q value for 11C decay.
b. What is the initial power output due to 11C decay?
c. What is the total energy released into the brain due to 11C decay?

Mathematical Analysis

14C undergoes beta-minus decay.
a. What is the maximum kinetic energy of the emitted electron?
b. Assuming the initial and final nuclei are at rest, and the neutrino mass is zero, find the kinetic energy of the emitted electron.

Mathematical Analysis

11Be undergoes beta-minus decay.
a. What is the maximum kinetic energy of the emitted electron?
b. Assuming the initial and final nuclei are at rest, and the neutrino mass is zero, find the kinetic energy of the emitted electron.

Mathematical Analysis

15O undergoes beta-plus decay.
a. What is the maximum kinetic energy of the emitted positron?
b. Assuming the initial and final nuclei are at rest, and the neutrino mass is zero, find the kinetic energy of the emitted positron.

Mathematical Analysis

Consider the neutrino capture reaction

a. Determine the end-product of the reaction.
b. What is the Q-value for the reaction?
c. What minimum value of kinetic energy must the neutrino have for this reaction to take place?

Mathematical Analysis

Consider the neutrino capture reaction

a. Determine the end-product of the reaction.
b. What is the Q-value for the reaction?
c. What minimum value of kinetic energy must the neutrino have for this reaction to take place?

Mathematical Analysis

Consider the anti-neutrino capture reaction

a. Determine the end-product of the reaction.
b. What is the Q-value for the reaction?
c. What minimum value of kinetic energy must the anti-neutrino have for this reaction to take place?

Mathematical Analysis

Consider the fission reaction:

a. Find Q for this reaction.
b. The total energy released by the fission bomb dropped on Hiroshima was equivalent to the chemical energy in 15 kilotons of TNT, approximately 60 x 1012 J. Based on this amount of energy, how many kilograms of uranium underwent fission in the bomb? (The bomb actually contained 64 kg of uranium.)
c. The fission reactions took place over about 10-12 s. What was the power of the Hiroshima bomb? Compare this power to the power output of the sun.

Mathematical Analysis

In addition to 235U, fission can also be induced in 239Pu. However, plutonium does not exist naturally. To create plutonium, 238U is bombarded with neutrons. (99.3% of all naturally occurring uranium is 238U, with almost all of the remainder 235U.)

a. Complete the above reaction, clearly showing how 239Pu is formed.
b. Find Q for the complete reaction.

Mathematical Analysis

Consider the fission reaction:

a. Find Q for this reaction.
b. A typical power plant generates about 20 MW of power. How many kg of plutonium must undergo fission per year to supply this energy? Assume about 30% of the energy released by fission is converted to electricity.

Mathematical Analysis

The proton-proton cycle (or p-p cycle) is responsible for energy production in the sun. The cycle consists of the following steps:

The complete cycle consists of step I twice, step II twice, followed by step III. Notice that these five steps lead to the creation of a single 4He nucleus (and two positrons).
a. Find Q for this cycle. (Hint: Rather than find the Q for each step of the cycle, just find the Q between the ultimate final state and the complete initial state of the cycle.)
b. The positron created by this cycle very rapidly annihilates with an electron in the sun. Add the energy released by this annihilation to the Q found above for the “total” Q of the p-p cycle.
c. Based on the total Q above, determine the number of p-p cycles occurring per second in the sun.

Mathematical Analysis

The carbon cycle is responsible for energy production in stars much larger than the sun. The cycle consists of the following steps:

Notice that the net effect of this cycle is creation of a single 4He nucleus (and two positrons). The carbon serves solely as a catalyst for the reaction. The carbon cycle progresses at a much faster rate than the p-p cycle described in a previous problem and is the dominant energy source for large stars.
a. Find Q for this cycle. (Hint: Rather than find the Q for each step of the cycle, just find the Q between the ultimate final state and the complete initial state of the cycle.)
b. The two positrons created by this cycle very rapidly annihilate with electrons. Add the energy released by these annihilations to the Q found above for the “total” Q of the carbon cycle.
c. Based on the total Q above, determine the number of carbon cycles occurring per second in a star ten times more powerful than the sun.

Mathematical Analysis

The most promising fusion reaction for electrical power generation is the deuterium (2H)-tritium (3H), or D-T, reaction:

Tritium is a radioactive form of hydrogen that would have to be artificially manufactured, but that process is technologically simple compared to creating the conditions needed for D-T fusion.
a. Find Q for this reaction.
b. The alpha particle carries about 20% and the neutron 80% of the released energy. The energy carried by the alpha (since it is charged) can be easily captured. Capturing the neutron’s energy is much more complicated. Calculate the velocity of the neutron.
c. One scheme for capturing the neutron’s energy is to have the reactor encircled in a 1 m thick blanket of liquid lithium. The following reaction would occur:

The alpha could then be easily captured and the 3H used as fuel for additional reactions. Find the Q for this neutron capture reaction.
d. Assuming all of this can be accomplished, how many kg of hydrogen must undergo fusion per year to supply a typical 20 MW power plant? Assume about 30% of the total energy released by fusion and neutron capture is converted to electricity.

Mathematical Analysis