Physics 17 Part R

The Nucleus and Radioactivity

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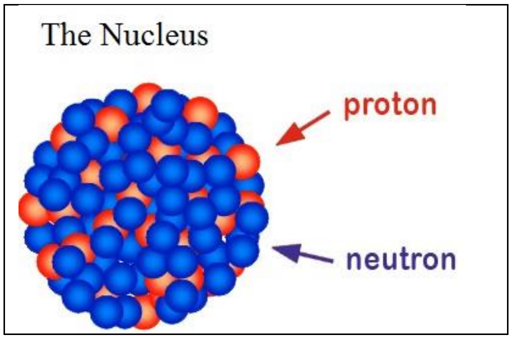
Video Lecture 1: Balancing Radioactive Decay Equations
Video Lecture 2: Half-Life Example Problem



At the center of all atoms there is a "nucleus," consisting to two types of particles called "nucleons." Nucleons are protons and neutrons that reside in the nucleus. They are no different than protons and neutrons that are found outside nuclei.

Ordinarily, packing protons so closely together would be impossible because of the electric force repulsion each exerts on the other protons, but there exists within nuclei a so-called "strong force" that overcomes the electric repulsion between protons, thereby allowing protons to bond to one another. The same force binds neutrons to other neutrons, and protons to neutrons. Thus, all of the nucleons in a nucleus pull on each other, each helping the others remain together to preserve the integrity of the nucleu--to keep it from flying apart.

Nucleus Symbol

Z = Number of protons
N = Number of neutrons
A = Number of nucleons
 = Z + N
X = Element symbol

$_{Z}X^{A}$

Element	Z	N	A	Symbol	Symbol	Symbol
carbon	6	6	12	$_{6}C^{12}$	carbon-12	C-12
nitrogen	7	8	15	$_{7}N^{15}$	nitrogen-15	N-15
uranium	92	146	238	$_{92}U^{238}$	uranium-238	U-238
helium	2	2	4	$_{2}He^{4}$	helium-4	He-4

Isotopes

Note in the table below that three types of carbon are listed; each has six protons, but there exist carbon nuclei with 6, 7 and 8 neutrons. These different types of carbon are called "isotopes." Two isotopes of uranium and two isotopes of radium are shown as further examples

Element	Z	N	A	Symbol	Alt Symbol
Carbon	6	6	12	$_6C^{12}$	carbon-12
Carbon	6	7	13	$_6C^{13}$	carbon-13
Carbon	6	8	14	$_6C^{14}$	carbon-14
Uranium	92	143	235	$_{92}U^{235}$	uranium-235
Uranium	92	146	238	$_{92}U^{238}$	uranium-238
Radium	88	138	226	$_{88}Ra^{226}$	radium-226
Radium	88	140	228	$_{88}Ra^{228}$	radium-228

Every element has a number of different isotopes, differing only in the numbers of neutrons in their nuclei. Isotopes have the same number of protons, and therefore atoms of that element have the same number and distribution of electrons orbiting the nucleus.

The chemical and electrical properties of an element depend entirely on the number and distribution of electrons orbiting the nucleus, so all of the isotopes of a given element are chemically and electrically indistinguishable. They generally *are*, however, distinguishable insofar as their varying instabilities are concerned.

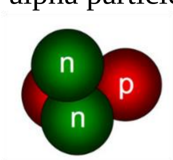
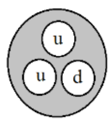
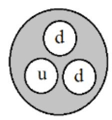
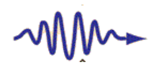
We will discuss below the radioactive consequences of these instabilities later, but first let's look at some examples of some of the fundamental particles that will be relevant to our coming study of radioactivity.

Elementary Particles and Their Symbols

We describe below the particles that commonly are emitted when unstable nuclei attempt to become more stable. First, let's discuss how we symbolize these particles.

Z = Charge as a multiple of e
A = Number of nucleons
X = Particle Symbol

$_zX^A$

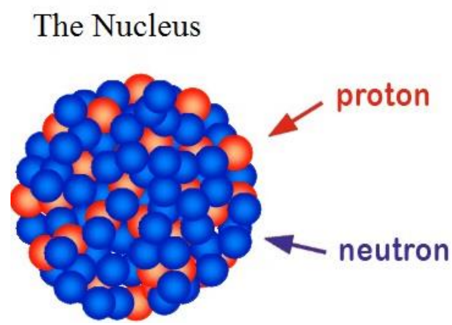
alpha particle  $_2\alpha^4$ The alpha particle . consists of two protons and two neutrons.	proton  $_1p^1$ Two up quarks and one down quark make a proton.	neutron  $_0n^1$ Two down quarks and one up quark make a neutron.	photon  $_0\nu^0$ Photons are charge-less, massless bundles of electromagnetic energy.
up quark $_{2/3}u^0$	down quark $_{-1/3}d$	beta particle $_{-1}\beta^0$ A beta particle is indistinguishable from an electron. Other symbol: β^- Another $_{-1}e^o$	positron $_1\beta^0$ Other symbol: β^+ Another symbol: $_1e^o$ The positron is also called an "anti-electron."

Radioactive Decay of Unstable Nuclei

If the number of neutrons in a nucleus, relative to the number of protons, is not just right--maybe too few neutrons, or too many protons, or maybe the nucleus was "excited" owing to heating, or the absorption of electromagnetic energy, the nucleus is said to be "unstable."

Unstable nuclei become stable by changing the neutron-proton ratio, which is accomplished by "radiating" away one or more of the particles listed above. Sometimes, the nucleus stabilizes itself by emitting a photon.

Whatever is the stabilizing mechanism, when this happens, the nucleus is said to be undergoing radioactive "decay."



If too many nucleons are stuffed inside a nucleus, or if there isn't just the right ratio of neutrons versus protons, the nucleus is unstable, and "radiation" of particles from within the nucleus occurs.

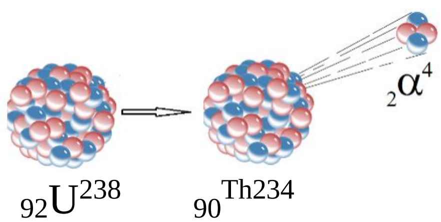
Balancing Radioactive Decay Equations

Two Rules:

1. The sum of subscripts before decay equals the sum after.
2. The sum of the superscripts before decay is the same as the sum after.

The first rule conserves the charge. The second one conserves the number of nucleons.

Proton emission	${}_{27}Co^{53} \rightarrow {}_{26}Fe^{52} + {}_{1}p^{1}$
Neutron emission	${}_{4}Be^{13} \rightarrow {}_{4}Be^{12} + {}_{0}n^{1}$
Beta particle emission	${}_{6}C^{14} \rightarrow {}_{7}N^{14} + {}_{-1}\beta^{0}$
Positron emission	${}_{12}Mg^{23} \rightarrow {}_{11}Na^{23} + {}_{1}\beta^{0}$
Alpha Decay	${}_{86}Rn^{222} \rightarrow {}_{84}Po^{218} + {}_{2}\alpha^{4}$



Illustrating alpha decay

Half-Life

The "half-life" of a radioactive substance is the amount of time it takes for half the sample to decay. Half-lives range from picoseconds to billions of years.	**Isotope**	**Half-Life**
	Iodine-131	8 days
	Radium-213	3 minutes
	Radium-226	1600 years
	Carbon-12	stable
	Carbon-14	5730 years
	Uranium-238	4.5 billion years

Example A:	Example B:
There are now 80 micrograms (μg) of radium-213 in a patient's thyroid gland. How many micrograms will there be 12 minutes from now? The half-life of Ra-213 is 3 minutes 12 minutes = 4 half-lives 4 halvings of 80 μg: 80→ 40→ 20→ 10→ 5 μg remaining	There are 15 picograms (pg), now, of a certain isotope. 6.0 minutes ago, there were 120 pg. What is this isotope's half-life? Answer: Three halvings: 120→60→30→15 6.0 minutes ÷ 3 = 2.0 minutes

Half-Life Equation

M_o = Initial mass
M = Later mass
T = Half-life
t = Elapsed time
$M = M_o (1/2)^{t/T}$

Example:

The half-life of a certain isotope is 40 minutes. There are now 80 micrograms (μg) of that isotope.

How many micrograms will there be 12 minutes from now?

M_o = 80 μg
t = 12 min
T = 40 min
M = ?
$M = M_o (1/2)^{t/T}$
$= 80 (1/2)^{12/40}$
= 64.98 μg

Example:

The half-life of a certain isotope is 14 years. There currently are 200 picograms of this isotope.

After how many years will only15 grams remain?

Two ways to obtain the answer:

Equation Solver:

$15 = 200\ (1/2)^{t/14}$
$t = 52.32$ years

Using logarithms:

$15/200 = (1/2)^{t/14}$
$\log (15/200) = \log (1/2)^{t/14}$
$-1.11249 = (t/14) \log (1/2)$
$t = 52.32$ years

Most students in this course typically are not expert in the use of logarithms; for them, I recommend solving problems like this using the solver.

Radiocarbon Dating

The ratio of carbon-12 to carbon-14 in living things is one trillion to one. Carbon-12 is stable, but carbon-14 decays; its half-life is 5730 years.

When an animal dies, the carbon-14 decays but the carbon-12 remains, so the ratio of carbon-12 to carbon-14 increases, doubling every 5730 years.

Example:

The ratio in a fossil is 4 trillion to one. How old is the fossil?

Answer: The ratio quadrupled, which is two doublings, so the fossil died two half-lives ago: 11,460 years old

The Shroud of Turin is described by some as an image depicting Jesus of Nazareth and further is believed to be the fabric in which he was wrapped after crucifixion, about two thousand years ago.

However, radiocarbon dating of the Shroud proves that the fibers used to make the cloth came from flax plants that died in the 14th century, seven hundred years ago, at about the same time the shroud was first "discovered" by Church authorities.

Induced Radioactivity and the Atomic Bomb

The "natural" radioactivity previously discussed occurs spontaneously without any external influences. "Induced" radioactive decay is caused when nuclei absorb photons, or are struck by neutrons, protons, or other particles, which cause (induce) them to decay. The second two of the three equations below, which correspond to the atomic bomb triggering sequence followed in the 1945 atomic bombing of Hiroshima, Japan, illustrate induced radioactivity.

<u>Example</u>:

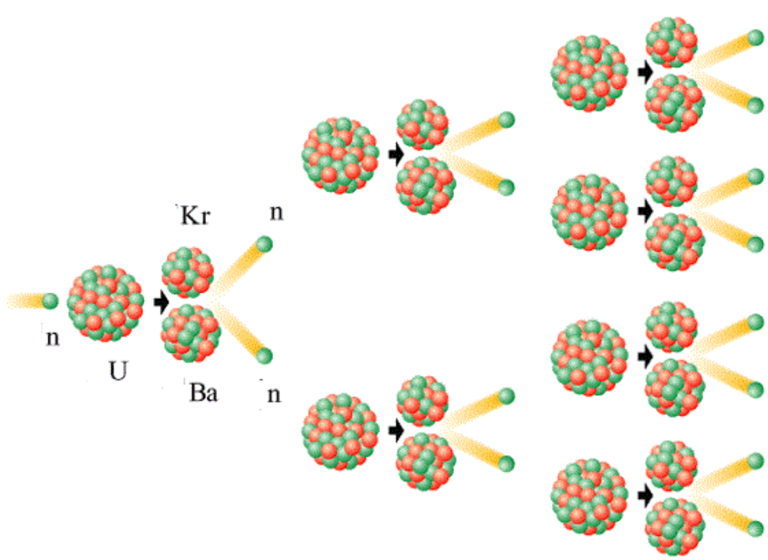
The three events in the sequence below represent the "trigger" that initiates the chain of "fissioning" uranium-235 that occurs when an atomic bomb is detonated.

$_{84}Po^{210} \rightarrow {}_{82}Pb^{206} + {}_{2}\alpha^{4}$

$_{2}\alpha^{4} + {}_{4}Be^{9} \rightarrow {}_{6}C^{12} + {}_{0}n^{1}$

$_{0}n^{1} + {}_{92}U^{235} \rightarrow {}_{36}Kr^{91} + {}_{56}Ba^{143} + {}_{0}n^{1} + {}_{0}n^{1}$ + E!!!

Note: one neutron in, and two neutrons out. Those two neutrons than go on to cause two more fissions and four more emitted neutrons. Then, those four neutrons create four more fissions and eight emitted neutrons, which created eight, then sixteen, then thirty-two more fissions, and so on, with each fission releasing energy, including electromagnetic and thermal energy. These events represent a "chain reaction," which is illustrated below.



Hiroshima, August, 1945

Radiation Dose

Define: Radiation Dose
Symbol: D
The “dose” an individual receives is the number of joules of radiation energy she absorbs, per kilogram of her mass:

Q = Quantity of Energy (in joules, J)
m = mass (in kilograms, kg)
D = Q/m

<u>Example:</u>

A 70-kg person absorbs 280 J of radiation. What dose does she receive?

D = 280 J / 70 kg
= 4 J/kg

Other Dose Units:

Let 1.0 rad = 0.01 J/kg
So, 1.0 J/kg = 100 rad
Previous example:
D = 4 J/kg
= 4 (100 rad)
= 400 rad

Biological Effects of Absorbed Radiation

Dose (rads)	Health Consequence
100	Vomiting within a week, hair falls out, then full recovery.
500	50% death within a week without care; with care, eventual recovery.
1100	50% die within two months, even assuming the best intensive medical care is given.

Spherically Symmetric Radiation

A spherically-symmetric radiation source has output power P. The radiation intensity, symbolized as I, is given below:

$$I = P/4\pi r^2$$

<u>Example</u>:

The output power of a spherically symmetric radiation source is 10.0 watts. A 60-kg person has a surface area of 0.70 m^2, and her distance from the source is 2.6 meters.

(a) What is the radiation intensity at her location?

$I = 10.0\ W/[4\pi\ (2.6\ m)^2]$
$= 0.118\ W/m^2$

(b) How much energy does her body absorb per second?

$0.118\ W/m^2\ (0.70\ m^2) = 0.0826\ W$
$= 0.0826\ J/s$

(c) How much radiation energy does she absorb in three hours?

3 hours = 3 (3600)
= 10,800 s

(0.0826 J/s) (10,800 s) = 892.08 J

(d) What dose (in rads) did she receive?

D = 100 (892.08 J/ 60 kg)
= 14.87 J/kg
= 1487 rad

Based on the statistics shown in the table above, death for this person is the likely outcome.