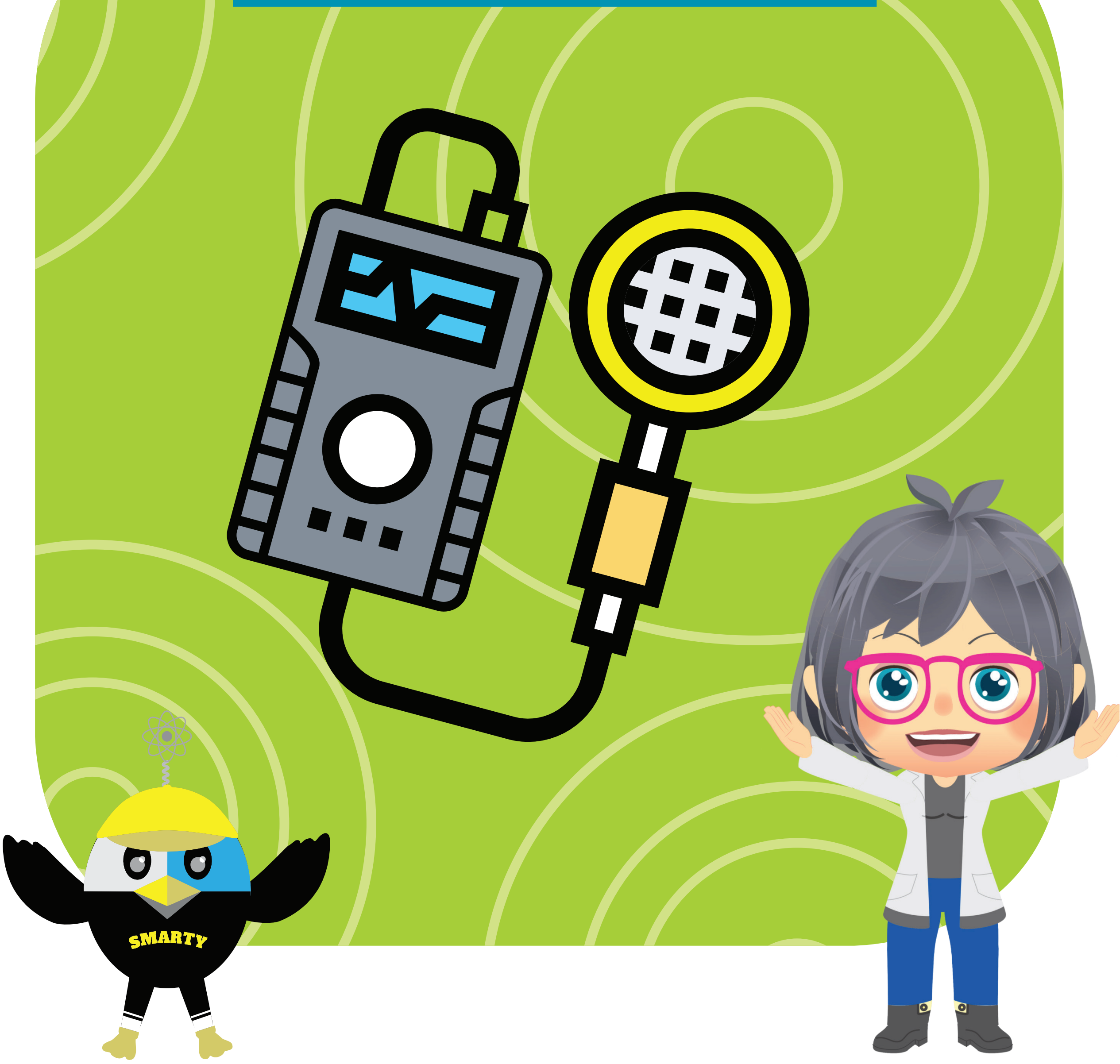
2 | NUCLEAR 101

Describing Radiation



Nuclear 101
Describing Radiation

A Resource Material for Secondary Students and Science Teachers

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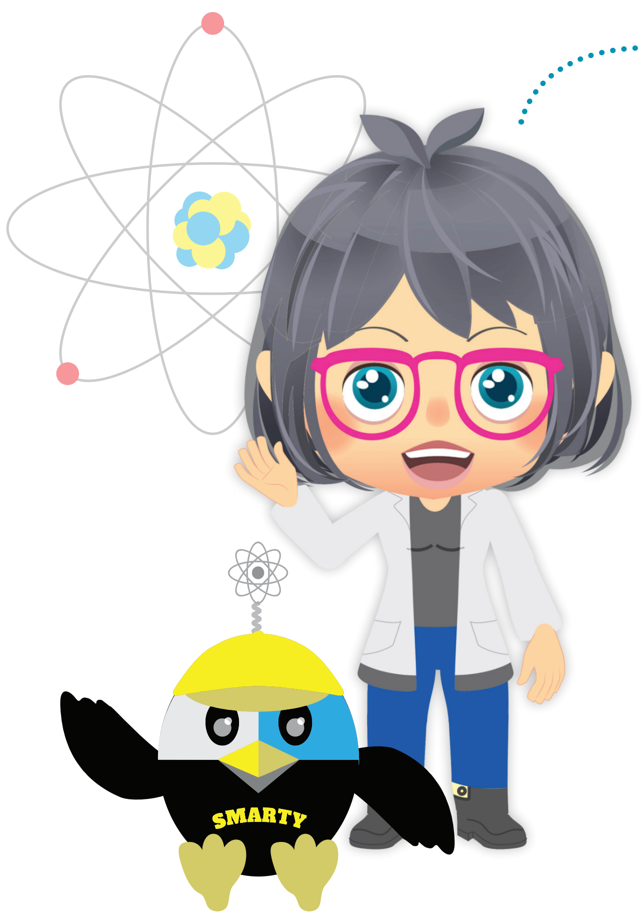


Hi there! I'm Radia! In this booklet, you will learn about:

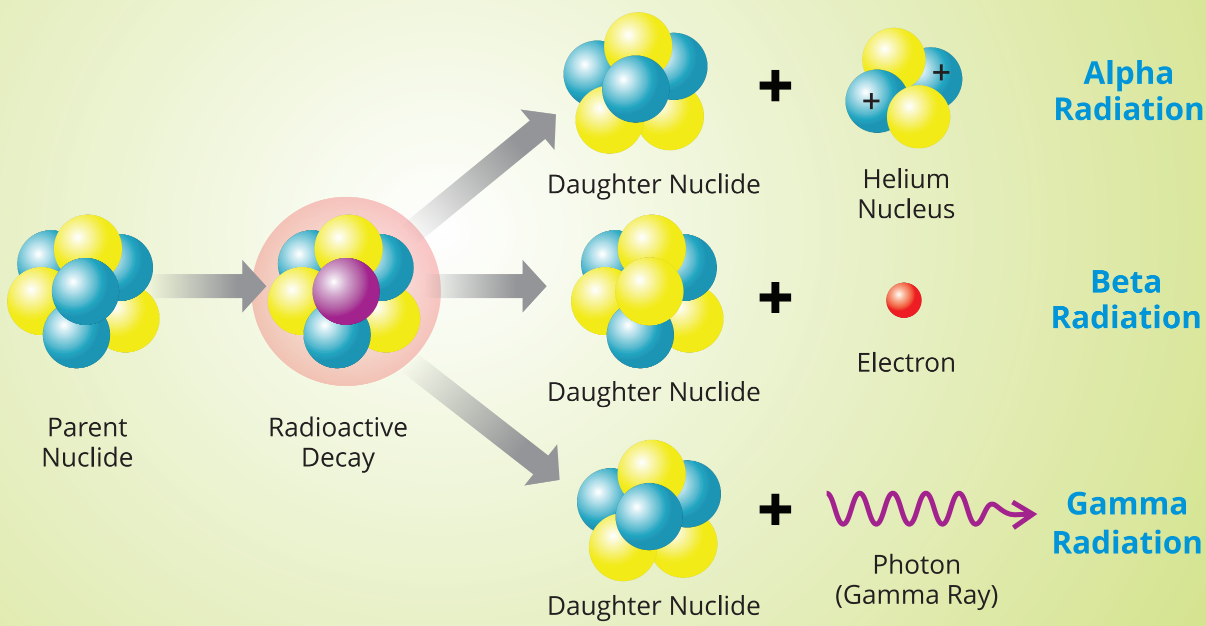
1. *Radioactivity and describe how radionuclides decay*
2. *The different types of detectors*
3. *The different quantities and units used in Radiation*
4. *Half-life of radionuclides*

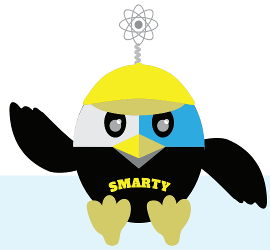
WHAT IS RADIOACTIVITY?

Radioactivity is the spontaneous nuclear transformations of unstable atoms that result in the formation of new elements. These transmutations are characterized by one of several different decay modes, including alpha-particle emission, beta-particle and positron emission, and orbital electron capture. These nuclear reactions may or may not be accompanied by gamma radiation. Radioactivity and radioactive properties of nuclides are determined by nuclear considerations only and are independent of the chemical and physical states of the radionuclide. Radioactive properties of atoms, therefore cannot be changed by any means and are unique to the respective radionuclides.

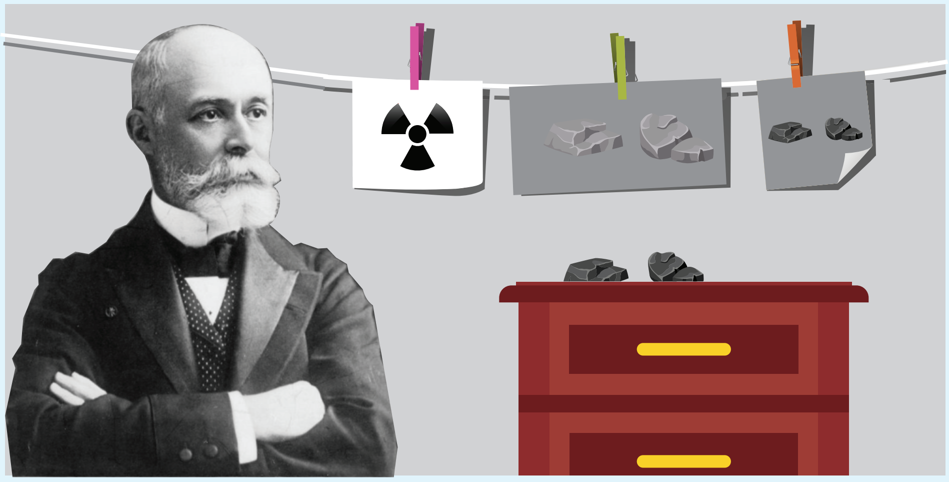
The exact mode of radioactive transformation depends on two factors: on the particular type of nuclear instability -that is, whether the neutron-to-proton ratio is too high or too low for the particular nuclide under consideration -and on the mass-energy relationship among the parent nucleus, daughter nucleus, and emitted particle

An unstable parent nuclide transforms into a new daughter nuclide. Alpha radiation, beta radiation and gamma radiation are the three most common decay modes.





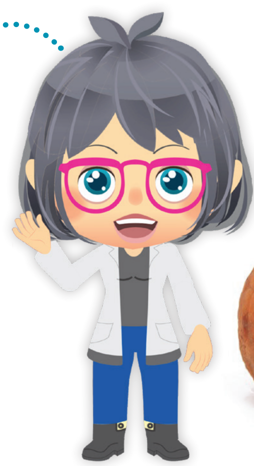
A Glimpse of History



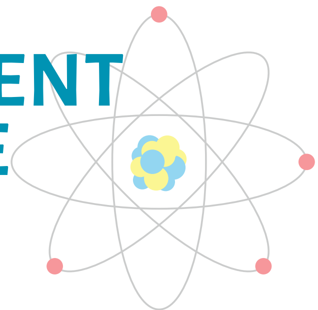
Radioactivity was first discovered by Antoine Henri Becquerel in 1896. Becquerel was experimenting with uranium, which was known to glow after being exposed to sunlight. Becquerel wanted to see if the glow was caused by rays of energy, like rays of light or X-rays. He placed a bit of uranium on a photographic plate after exposing the uranium to sunlight. The plate was similar to the film that is used today to take X-rays, and Becquerel expected the uranium to leave an image on the plate. The next day, there was an image on the plate, just as Becquerel expected. This meant that uranium gives off rays after being exposed to sunlight.

Repeating his experiment to confirm the results, he placed more uranium on a photographic plate. It turned cloudy on the day of his experiment, so he kept the plate and uranium in a drawer to try again the next day. He wasn't expecting the uranium to leave an image on the plate without first being exposed to sunlight. To his surprise there was an image on the plate in the drawer the next day. Becquerel had discovered that uranium gives off rays on its own.

*You might associate decay with the photo on the right. But it has a different meaning when it comes to atoms. **Decay** in nuclear science refers to changes in an atom's nucleus.*



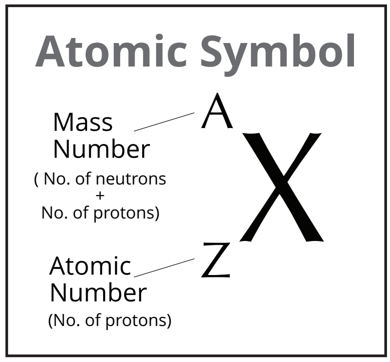
WHAT ARE THE DIFFERENT TYPES OF RADIOACTIVE DECAY?

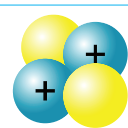
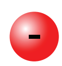
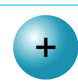


There are five different types or modes of radioactive decay:

1. Alpha decay
2. Beta decay
3. Gamma decay
4. Positron emission
5. Electron capture

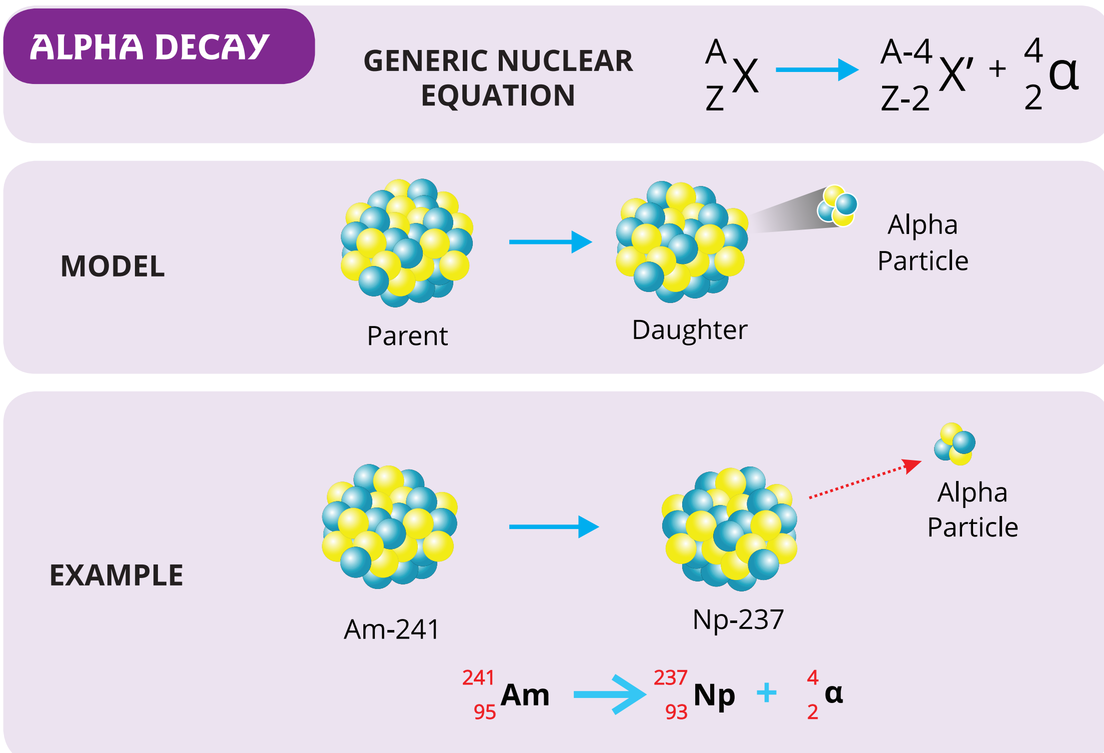
Each of this transformation is described by a **nuclear equation**. Below are common symbols and representations used in these equations:



Name	Symbol(s)	Representation
Alpha particle	${}^{4}_{2}He$ or ${}^{4}_{2}\alpha$	
Beta particle	${}^{0}_{1}e$ or ${}^{0}_{-1}\beta$	
Positron	${}^{0}_{+1}e$ or ${}^{0}_{+1}$	
Proton	${}^{1}_{1}H$ or ${}^{1}_{1}p$	
Neutron	${}^{1}_{0}n$	
Gamma ray	γ	 γ

Alpha Decay

An **alpha particle** is a highly energetic helium nucleus that is emitted from the nucleus of an unstable atom when the neutron-to-proton ration is too low. It is a positively charged, massive particle consisting of an assembly of two protons and two neutrons. Since atomic numbers and mass numbers are conserved in alpha transitions, it follows that the result of alpha emission is a daughter whose atomic number is two less than that of the parent and whose mass number is four less than that of the parent.

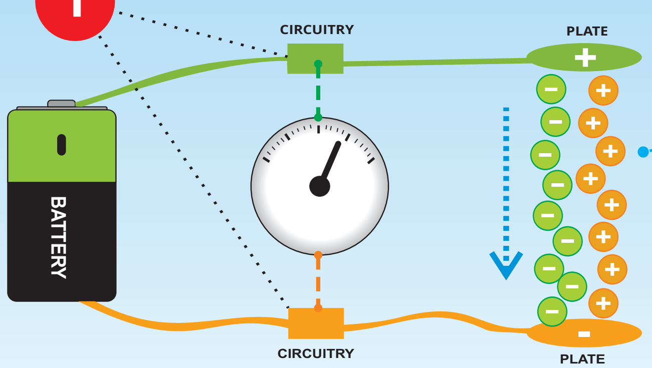


Alpha particles are relatively slow and heavy compared to other forms of nuclear radiation. Because they are highly ionizing, they are unable to penetrate very far through matter and are brought to rest by few a centimeters of air or a thin sheet of paper. Materials that emit alpha particles are potentially dangerous if they are inhaled or swallowed, but external exposure generally does not pose a danger.

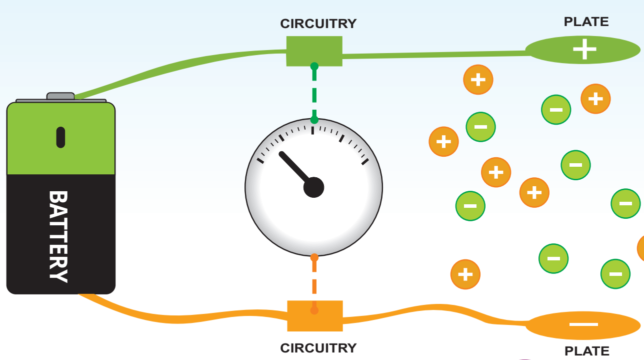
INSIDE SMOKE ALARMS

HOW SMOKE ALARMS WORK

1 Two metal plates called electrodes are connected to a battery.

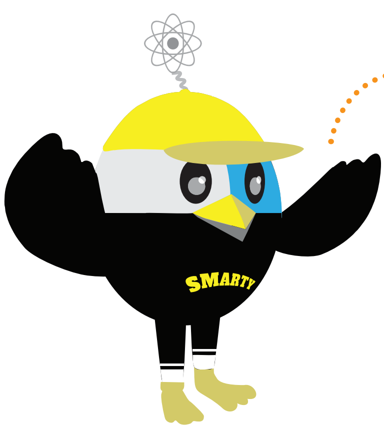


2 Americium-241 converts air into positive and negative ions. Positive ions are attracted to the negative electrodes and negative ions are attracted to the positive electrodes.



3 When smoke enters the smoke alarm, the ions bond with the smoke, breaking the path of electricity

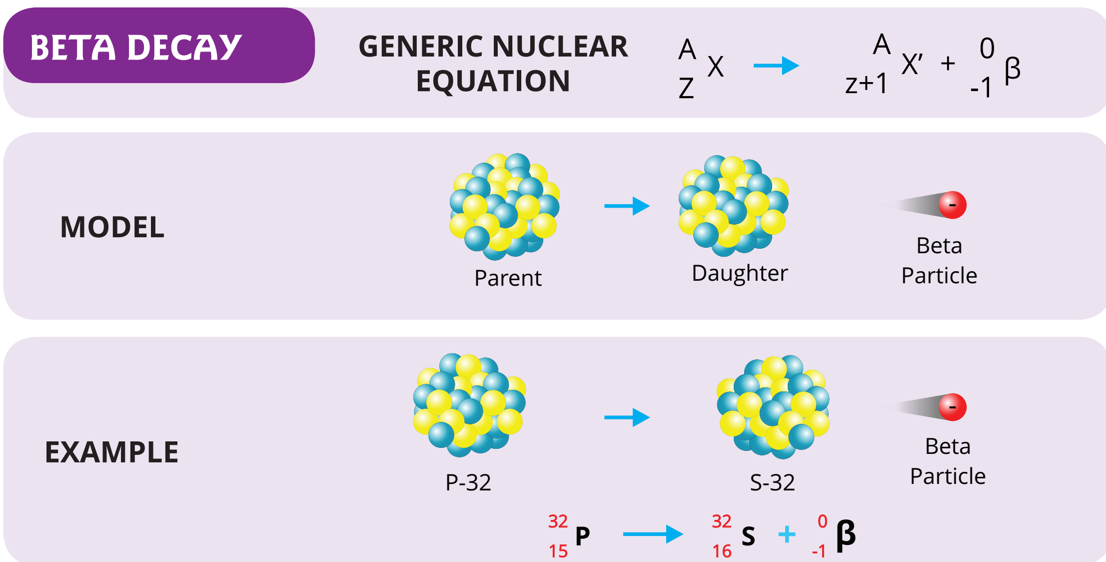
When the flow of electricity is reduced, the alarm goes off.



Alpha emission is used in smoke detectors. The radiation given off by Americium as it decays is lower than the background radiation.

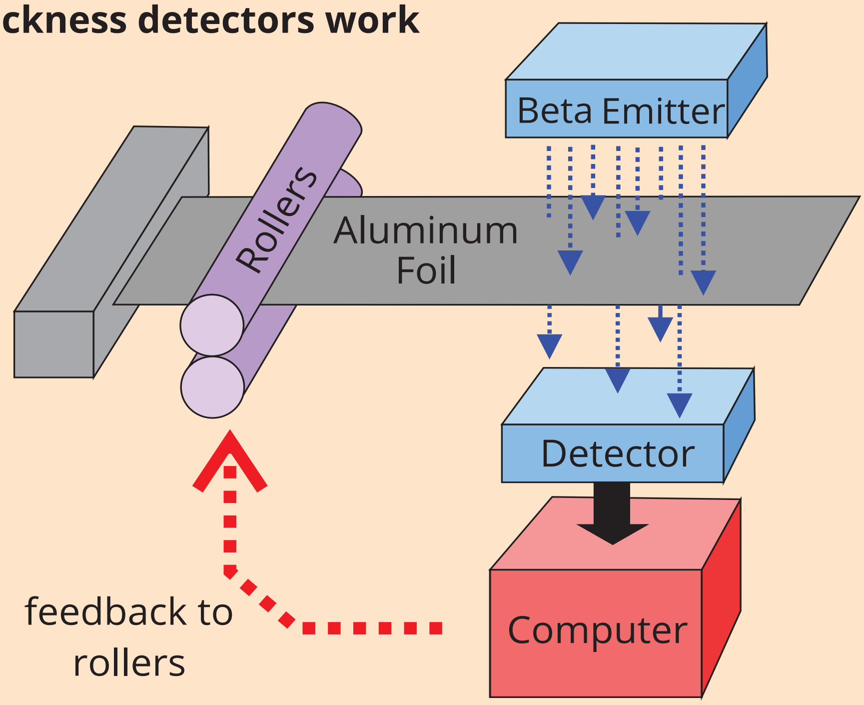
Beta Decay

In **beta decay,** a nucleus simultaneously emits a beta particle. This particle is created at the moment of nuclear decay. A beta particle is a negatively charged particle that is indistinguishable from an ordinary electron; it is ejected from the nucleus of an unstable atom whose neutron-to-proton ratio is too high. The particle has a single negative electric charge, and therefore also called a negatron. The beta decay occurs among those nuclides that have a surplus of neutrons. The excess neutron will be converted into a proton followed by the emission of a beta particle. The atomic number of the daughter nucleus increases while the mass number remains the same.



Beta particles, being less ionizing than alpha particles, can travel through many centimeters or even meters of air and through millimeters of skin or tissue. External exposure to high energy beta radiation can cause burns and tissue damage, along with other symptoms of radiation sickness. If beta-emitting radionuclides are inhaled or ingested, they can also do damage to internal cells and organs.

How thickness detectors work



Radiation from the beta emitter is transmitted to the aluminum foil, while some beta particles are being absorbed, others are passing through the aluminum foil and then detected by the detector. The amount of radiation arriving at the detector is then monitored by a computer, giving feedback to the rollers once pulses have been received. These rollers will then be moving at a desired gap, adjusting to maintain the thickness of the aluminum foil.

The penetrating power of beta particles provides a range of useful applications which include:

- Thickness detectors for the quality control of thin materials like paper and plastic sheets.
- Treatment of eye and bone cancers, strontium-90 (Sr-90) or strontium-89 (Sr-89) are commonly used.
- Tritium is used in some phosphorescent lighting typically for emergency lighting as it requires no power.
- Fluorine-18 (F-18) is commonly used as a tracer for positron emission tomography (PET).

Gamma Decay

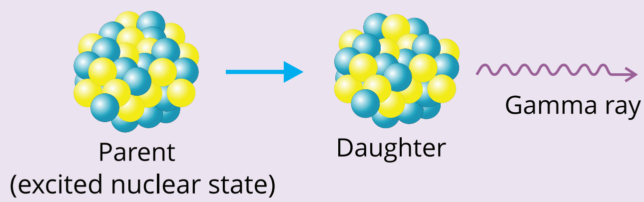
Gamma rays are monochromatic electromagnetic radiations that are emitted from the nuclei of excited atoms following radioactive transformations; they provide a mechanism to get rid of the excited nuclei of their excitation energy without affecting either the atomic number or the atomic mass number of the atom.

GAMMA DECAY

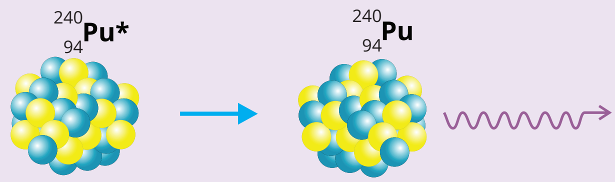
GENERIC NUCLEAR EQUATION

$${}^{A}_{Z}X^{*} \xrightarrow{\text{Relaxation}} {}^{A}_{Z}X' + {}^{0}_{0}\gamma$$

MODEL



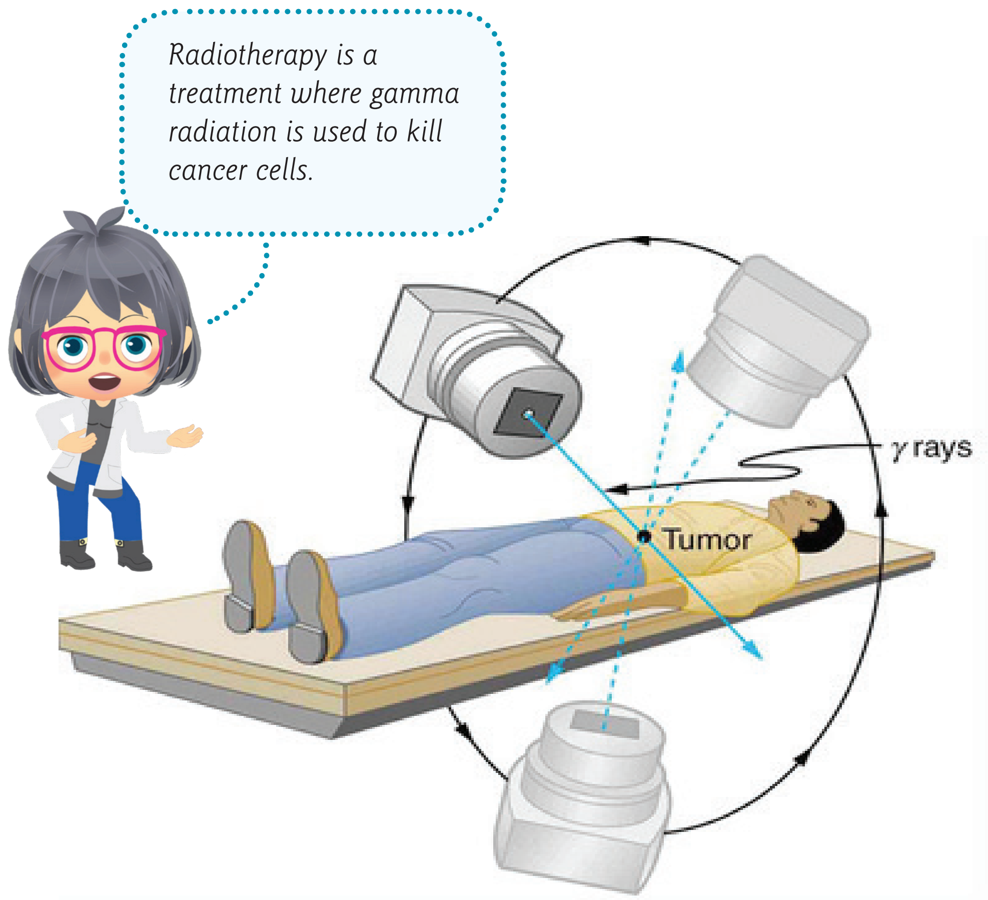
EXAMPLE



$${}^{240}_{94}Pu^{*} \rightarrow {}^{240}_{94}Pu + {}^{0}_{-1}\gamma$$

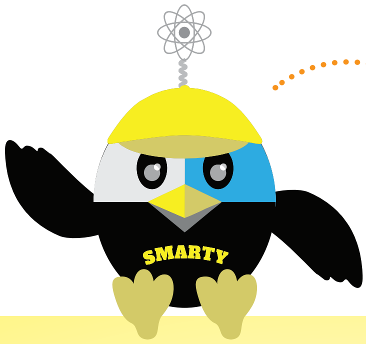
Gamma radiation is highly penetrating and interacts with matter through ionization via three common processes; photoelectric effect, Compton scattering or pair production. Due to their high penetration power, the impact of gamma radiation can occur throughout a body; they are, however, less ionizing than alpha particles. Gamma radiation is considered an external hazard with regards to radiation protection.

Similar to all exposure to ionizing radiation, high exposures can cause direct acute effects through immediate damage to cells. Low levels of exposure carry a stochastic health risk where the probability of cancer induction rises with increased exposure. Gamma radiation is released from many of the radioisotopes found in the natural radiation decay series of uranium, thorium and actinium as well as emitted by the naturally occurring radioisotopes potassium-40 and carbon-14. These are found in all rocks and soil and even in our food and water. Artificial sources of gamma radiation are produced by fission in nuclear reactors, high energy physics experiments, nuclear explosions and accidents.

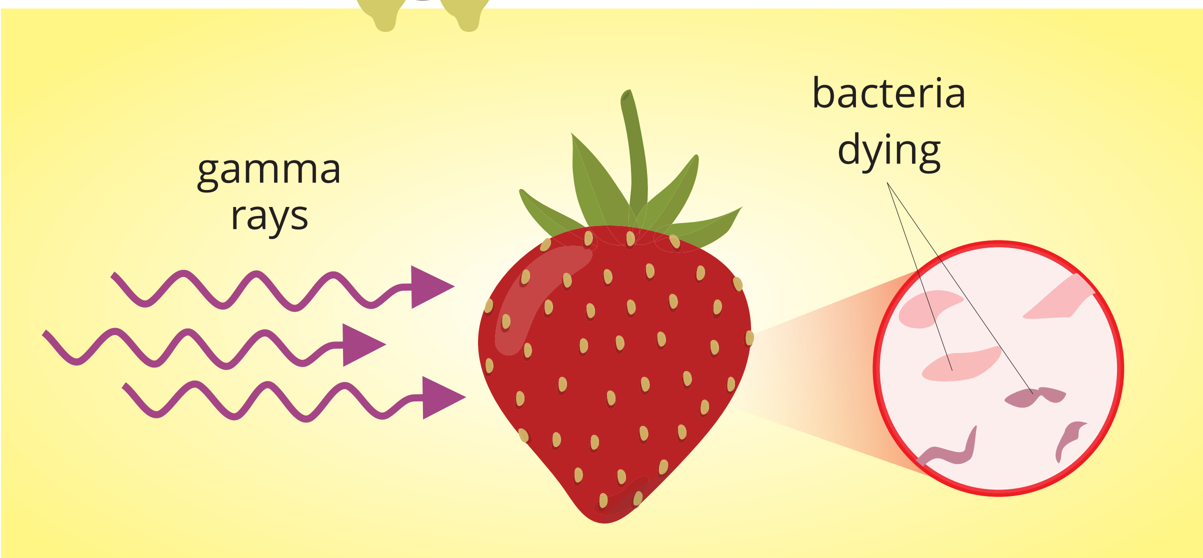


Gamma radiation has various medical and industrial applications, some of which are as follows:

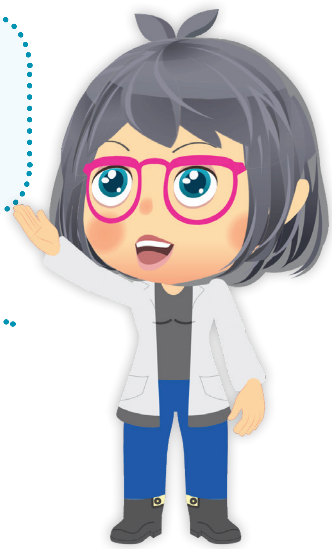
- Sterilization of medical equipment
- Pasteurization, via irradiation of certain foodstuffs
- Level or thickness gauges (i.e. food packaging, steel mills)
- Industrial radiography
- Measurement and control of the flow of liquids in industrial processes
- Investigation of subterranean strata
- Measurement of soil moisture-density at construction sites
- Level gauges for packaging of food, drugs and other products
- Tc-99m is the most widely used radioactive isotope for medical diagnostic studies
- Different chemical forms are used for brain, bone, liver, spleen and kidney imaging. It is also used for blood flow studies
- Fluid level and density gauges
- Aircraft fuel gauges



Gamma radiation is used in irradiating fruits to inhibit the growth of bacteria, destroy viruses, microorganisms and even insects that could be present in the food.



Irradiated food does not become radioactive! So they are safe to eat.



Positron Emission

A positron (also called antielectron) is an antimatter version of an electron. It is a particle of matter with the same mass as an electron but an opposite charge. It has the same mass and spin as an electron. They are the antiparticles of electrons. However, it has a positive electric charge, whereas an electron has a negative charge.

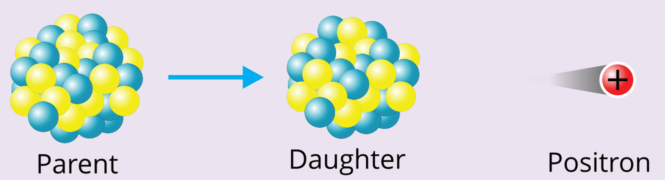
The emission of a positron occurs when there is a very small neutron to proton ratio. The proton in a radioactive nucleus converts into a neutron and a positron is emitted.

POSITRON EMISSION

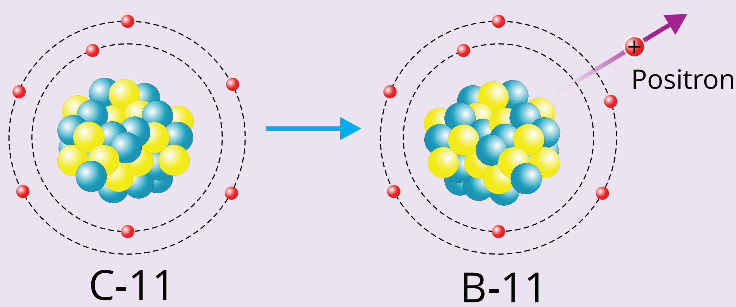
GENERIC NUCLEAR EQUATION

$$^{A}_{Z}X \rightarrow \,^{A}_{Z-1}X' + \,^{0}_{+1}\beta$$

MODEL



EXAMPLE



$$^{11}_{6}C \rightarrow \,^{11}_{5}B + \,^{0}_{+1}\beta$$

Electron Capture

A process in which a proton-rich nucleus of an atom captures an inner electron usually from the K or L electron shell. This process thereby changes a proton to a neutron and causes the emission of characteristic X-rays and an Auger electron.

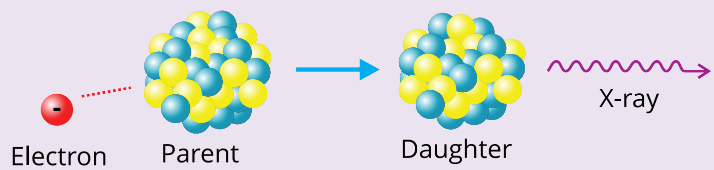
The capture of an electron will lead to a decrease in the atomic number (number of protons), increase in the number of neutrons and no change in the mass number.

ELECTRON CAPTURE

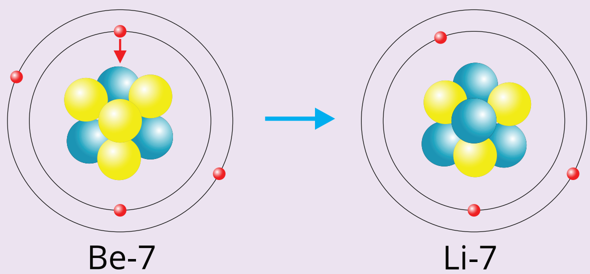
GENERIC NUCLEAR EQUATION

$${}^{A}_{Z}X + {}^{0}_{-1}e \rightarrow {}^{A}_{Z-1}X' + \text{X-ray}$$

MODEL



EXAMPLE



$${}^{7}_{4}\mathbf{Be} + {}^{0}_{-1}\beta \rightarrow {}^{7}_{3}\mathbf{Li}$$

The example above shows the electron capture decay of beryllium-7 (Be-7). Be-7 has 4 protons and 3 neutrons, therefore the neutron proton ratio is less than 1. The excess proton will capture the nearest electron changing itself to a neutron. This event will then lead to emission of X-rays and an auger electron.

HOW DO WE DETECT RADIATION?

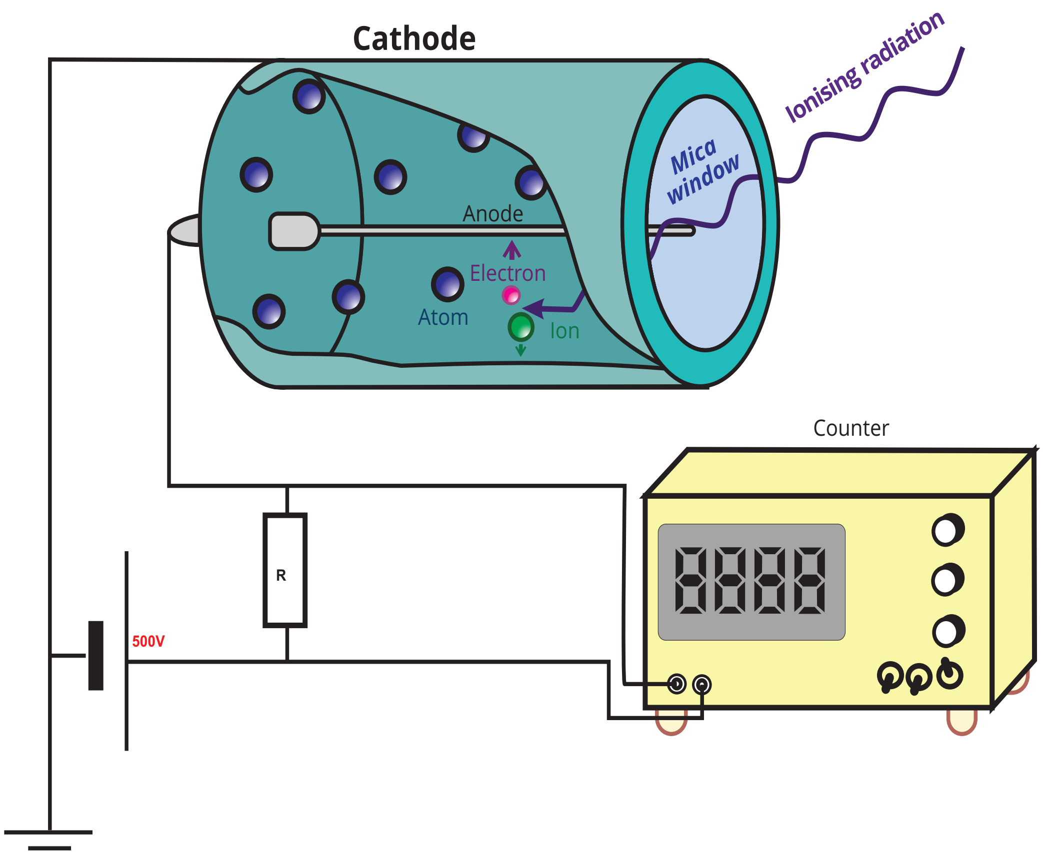
Radiation cannot be detected by human senses. It cannot be seen, heard, smelled, tasted, or felt. For these reasons, simple visual inspection is insufficient to identify radioactive materials, and radiation sources can be virtually impossible to recognize without special markings. For such problems to be addressed, a variety of instruments were developed to detect and measure radiation.

The most common handheld or portable instruments are:

1. **Personal Radiation Detector** – is a wearable gamma/ neutron radiation detector, approximately the size of a pager. When exposed to elevated radiation levels, the device alarms with flashing lights, sound, and/or vibrations.

2. **Geiger-Mueller (GM) tube, also called a Geiger Counter** – A GM tube is a gas filled device that, when a high voltage is applied, creates an electrical pulse when radiation interacts with the wall or gas in the tube. These pulses are converted to a reading on the instrument meter. If the instrument has a speaker, the pulses also give an audible click. Common readout units are roentgens/hour (R/hr), milliroentgens per hour (mR/hr), rem per hour (rem/hr), millirem per hour (mrem/hr), and counts per minute (cpm). GM probes are most often used with handheld radiation survey instruments for contamination purposes. However, energy-compensated GM tubes may be employed for exposure measurements. Further, often the meters used with a GM probe will also accommodate other radiation-detection probes. For example, a zinc sulfide (ZnS) scintillator probe, which is sensitive to just alpha radiation, is often used for field measurements where alpha-emitting radioactive materials need to be measured.

Detection Mechanism of Gas-Filled Detectors



3. **Sodium Iodide Detectors** – A solid crystal of sodium iodide creates a pulse of light when radiation interacts with it. This pulse of light is converted to an electrical signal by a photomultiplier tube (PMT), which gives a reading on the instrument meter. The pulse of light is proportional to the amount of light and the energy deposited in the crystal. These instruments most often have upper and lower discriminator circuits and, when used correctly as single-channel analyzers, can provide information on the gamma energy and identify the radioactive material. If the instrument has a speaker, the pulses also give an audible click, a useful feature when looking for a lost source.

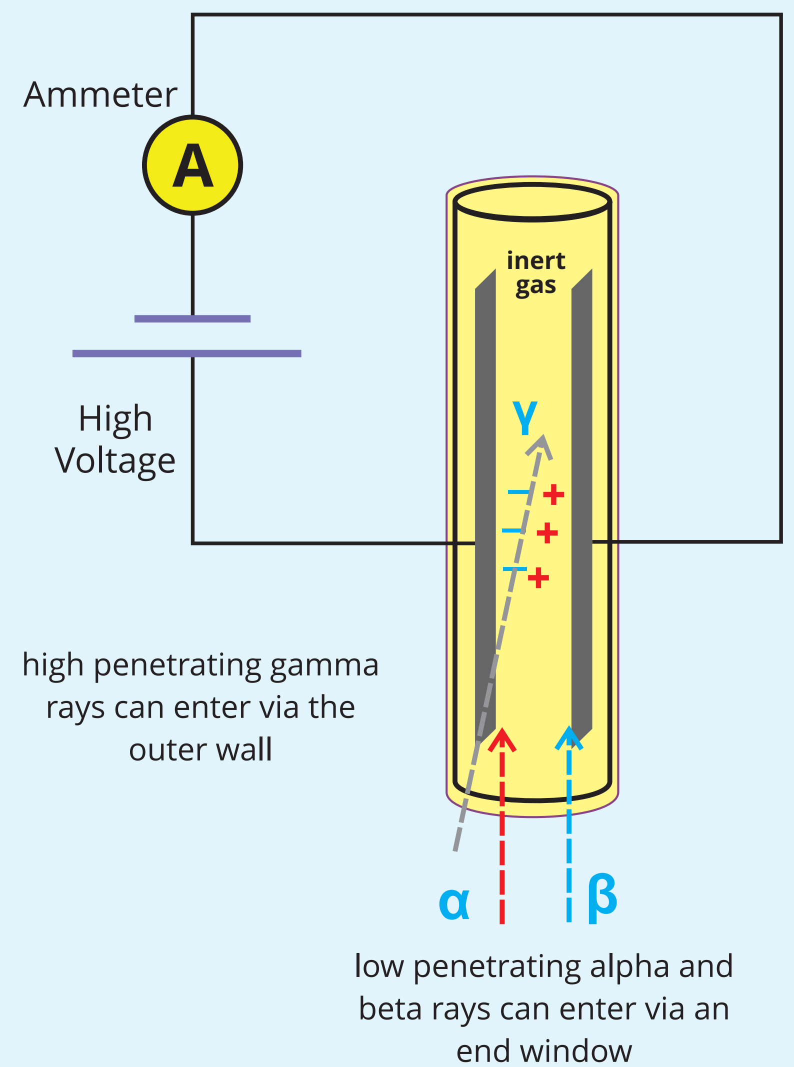
Sodium Iodide Detector

Multi-channel Analyzer

4. **Portable Multichannel Analyzer** – A sodium iodide crystal and PMT described above, coupled with a small multichannel analyzer (MCA) electronics package, are becoming much more affordable and common. When gamma-ray data libraries and automatic gamma-ray energy identification procedures are employed, these handheld instruments can automatically identify and display the type of radioactive materials present. This feature is very useful when dealing with unknown sources.

5. **Ionization Chamber –** Air-filled chamber with an electrically conductive inner wall and central anode and a relatively low applied voltage. When primary ion pairs are formed in the air volume, from x-ray or gamma radiation interactions in the chamber wall, the central anode collects the electrons and a small current is generated. This in turn is measured by an electrometer circuit and displayed digitally or on an analog meter. These instruments must be calibrated properly to a traceable radiation source and are designed to provide an accurate measure of absorbed dose to air which, through appropriate conversion factors, can be related to dose to tissue.

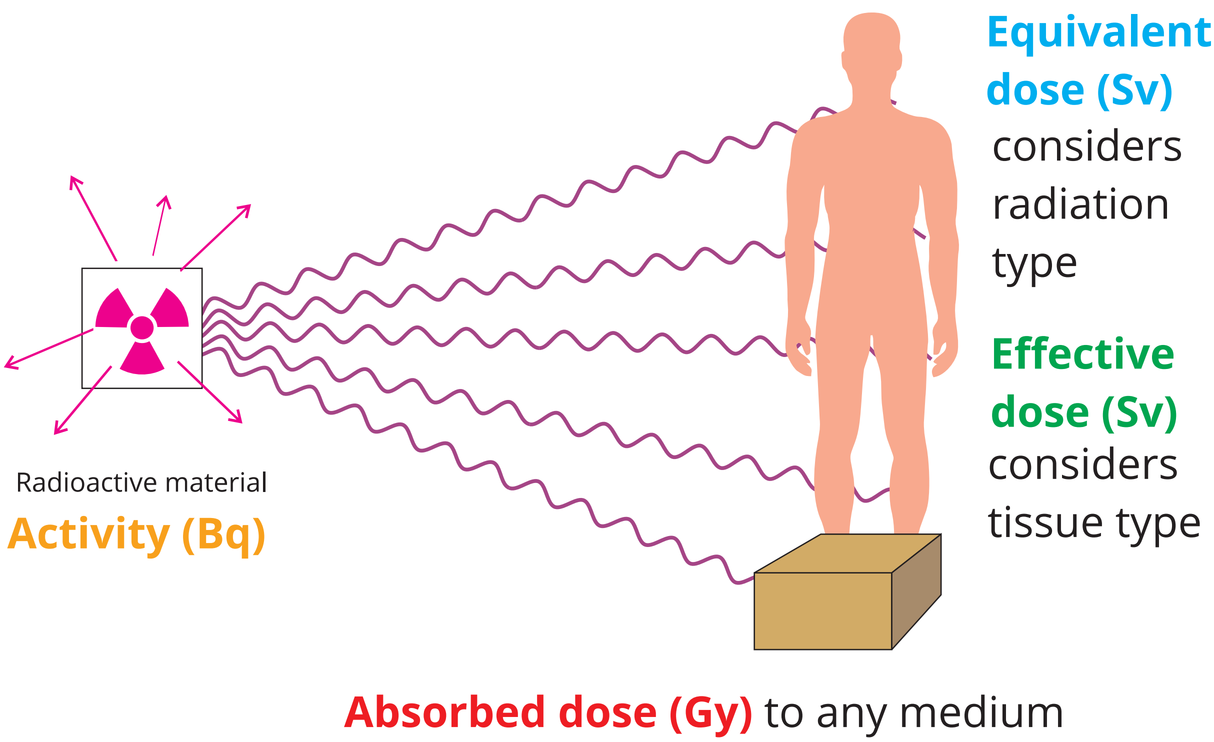
Detection Mechanism of an Ionization Chamber



WHAT ARE THE DIFFERENT QUANTITIES AND UNITS USED IN RADIATION?

There are two systems of units which are commonly used by scientists to describe quantities related to ionizing radiation – (a) Special Units and (b) SI (System Internationale) Units. Special Units are used by most regulatory agencies in the US, while the SI units are used in the rest of the world.

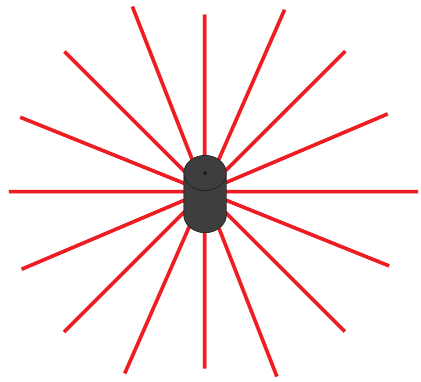
QUANTITY	SPECIAL UNITS	SI UNITS
Activity or Radioactivity	roentgen (R) curie (Ci)	becquerel (Bq)
Radiation Absorbed Dose	radiation absorbed dose (rad)	gray (Gy)
Equivalent Dose or Effective Dose	roentgen-equivalent man (rem)	sievert (Sv)



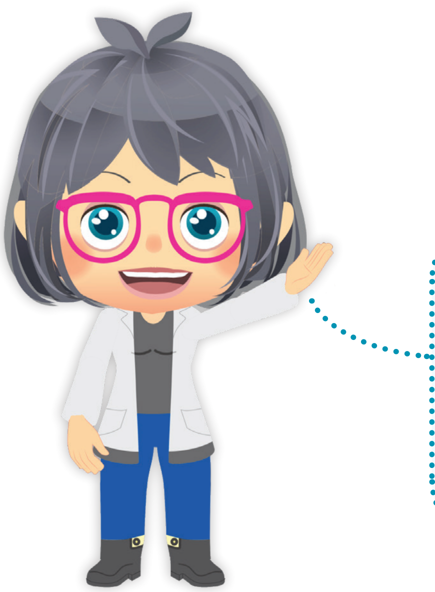
Activity or Radioactivity

Quantity of a radioactive material is expressed as the number of nuclear transformations (or disintegrations) that occur in a sample per unit time. The term for quantity of radioactive material is activity. Activity, expressed in units of becquerel (Bq), tells how many unstable nuclei decay or disintegrate in a second and emit radiation. High activity means high radiation intensity.

Radioactive waste: **low activity**



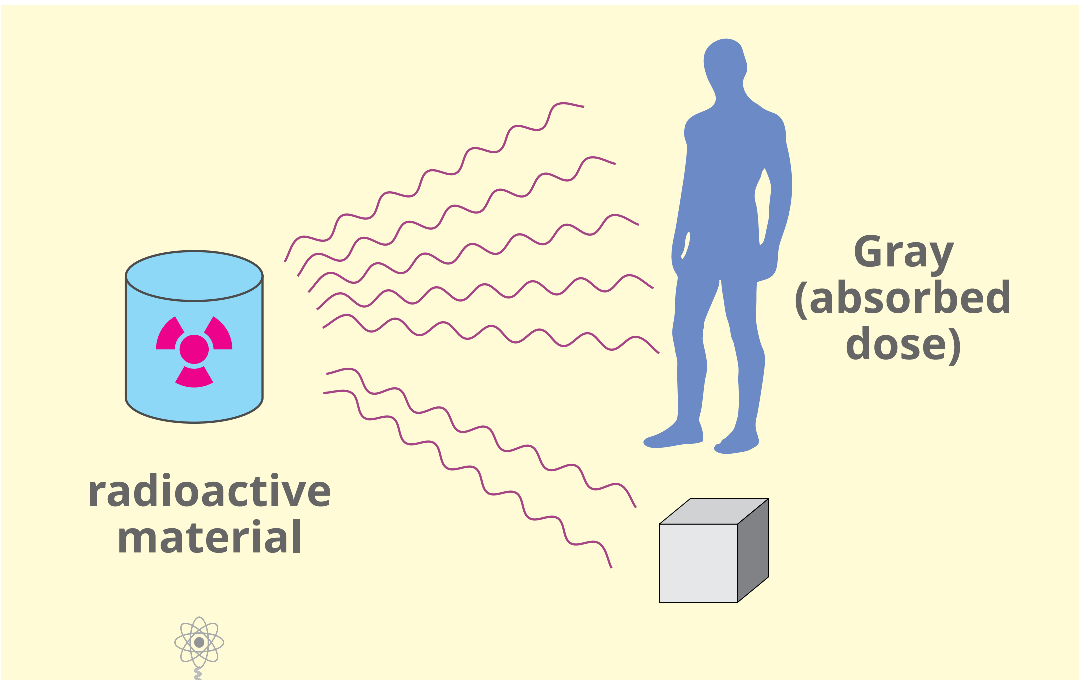
Uranium fuel pellet: **high activity**

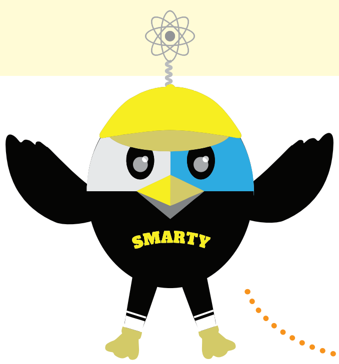


The activity of a radioactive material is not proportional to the size of the material itself. We could have a large container, but since it only contains low level radioactive waste, the activity is very low. On the other hand, we can have a material as small as a fingertip but has a high activity!

Radiation Absorbed Dose

When ionizing radiation passes through matter, its energy is absorbed there. Absorbed dose is a measure of the amount of energy imparted in a material by ionizing radiation. Absorbed dose is expressed as energy absorbed per unit mass of a material. The unit is the joule per kilogram (J/kg) and is given the name gray (Gy). Different types of ionizing radiation deposit different amounts of energy to different materials including humans.





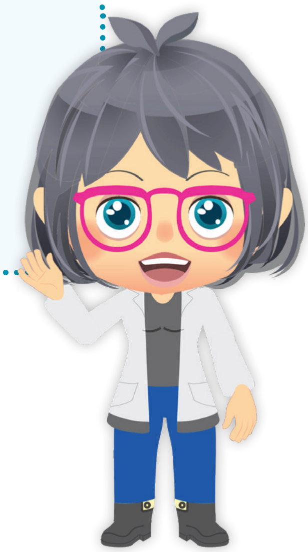
The amount of energy transferred per unit mass of material is the absorbed dose of which the unit used is the gray (Gy).

Equivalent Dose

Equivalent dose is a measure of the biological effect of radiation on a tissue or organ and takes into account the type of radiation. The unit is the sievert (Sv), but doses are usually measured in millisieverts (mSv) or microsieverts (μSv). Equivalent dose is obtained by multiplying the absorbed dose to a modifying factor called **Radiation Weighting Factor (WR)** which reflects the relative biological effect of ionizing radiation.

TYPE OF IONIZING RADIATION	RADIATION WEIGHTING FACTOR, WR
X rays	1
γ rays	1
β particles (electrons or positrons)	1
α particles, fission fragments, heavy ions	20
Neutrons: < 10 keV 10 keV– 100 keV > 100 keV – 2 MeV > 2 MeV – 20 MeV > 20 MeV	 5 10 20 10 5

From the table, which type of ionizing radiation do you think will have a more pronounced biological effect on organs and/ or tissues?



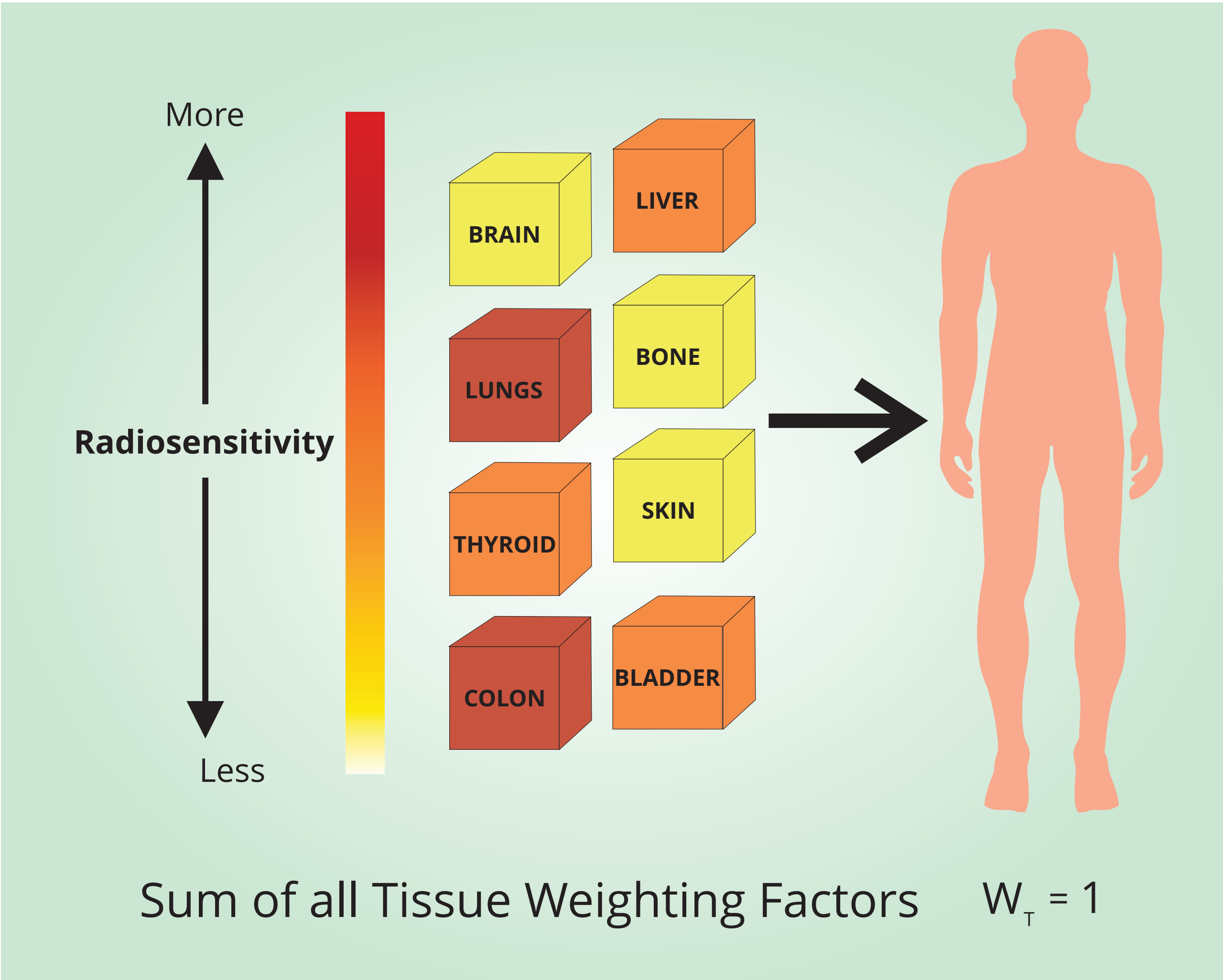
Effective Dose

Effective dose is a measure of the biological effect of radiation on the whole body. It takes into account the equivalent dose and the differing radiosensitivities of body tissues. Organs differ in sensitivity to ionizing radiation. Like equivalent dose, effective dose is also expressed in units of sievert (Sv).

Effective Dose is intended to reflect the total biological effect of a given exposure on a human. It is a weighted average of the individual doses to a number of important tissues. It is obtained by multiplying the equivalent dose to a modifying factor called Tissue Weighting Factor (WT).

ORGAN/TISSUE	NUMBER OF TISSUES	TISSUE WEIGHTING FACTOR, WT	TOTAL CONTRIBUTION
Bone marrow (red), colon, lung, stomach, breast, remainder tissues*	6	0.12	0.72
Gonads	1	0.08	0.08
Bladder, oesophagus, liver, thyroid	4	0.04	0.16
Bone surface, brain, salivary glands, skin	4	0.01	0.04
		Total	**1.00**

**The specified remainder tissues (14 in total, 13 in each sex) are: adrenals, extrathoracic tissue, gall bladder, heart, kidneys, lymphatic nodes, muscle, oral mucosa, pancreas, prostate, small intestine, spleen, thymus, uterus/cervix*



The tissue weighting factor is 1 if a person receives a whole body dose. But in medical imaging, only a portion of the body is being exposed to radiation. Tissue weighting factors allow comparison of a whole body dose to a partial body dose and also allow comparison between doses to tissues of varying radiosensitivities. Note that tissues that are more sensitive to ionizing radiation have higher weighting factors.

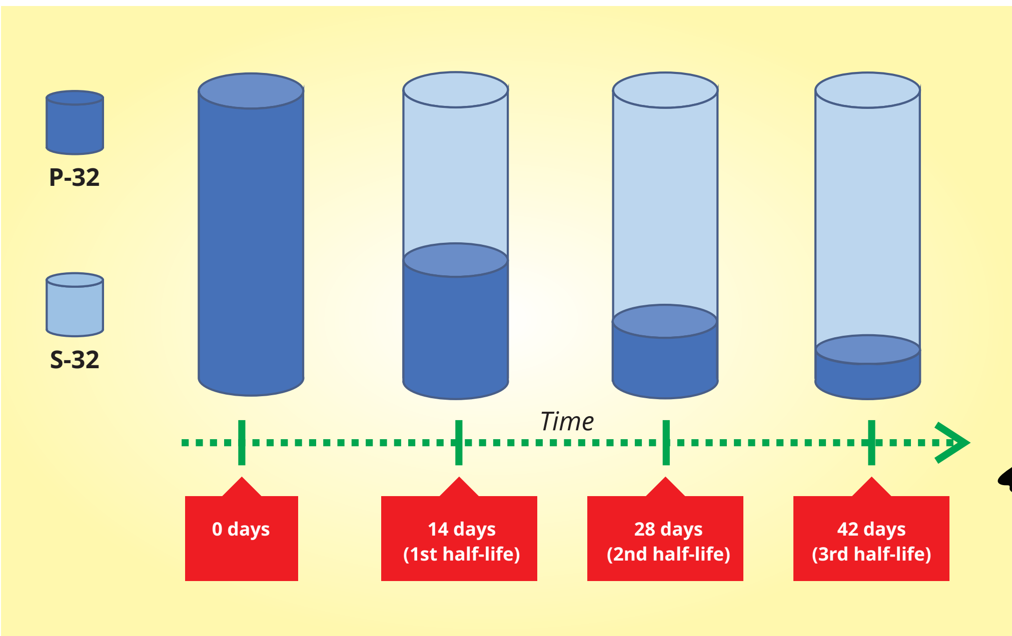
From the table, which organ/ tissue do you think is most sensitive to radiation?

WHAT IS HALF-LIFE?

A radioisotope decays and changes to a different element at a constant rate. The rate is measured in a unit called the half-life. This is the length of time it takes for half of a given amount of the radioisotope to decay. This rate is always the same for a given radioisotope regardless of temperature, pressure, or other conditions outside the nuclei of its atoms.

Rate of Radioactive Decay

A radioactive sample phosphorus-32 (P-32) has a half-life of 14.3 days, how much amount of P-32 sample will remain after 3 half-lives?



The half-life of P-32 is 14 days. After 14 days, half of the original amount of P-32 has decayed, so only half remains. After another 14 days, half of the remaining amount is still left, and so the decay continues.

Each half-life will make the radioactive sample 50% less than the previous amount of activity.

$$A = A_0 \cdot \left(\frac{1}{2}\right)^{t/h}$$

A: final amount or activity

A_0: initial amount or activity

t: time

h: half-life

$\frac{1}{2}$: This is the split factor

Half-lives of Some Radioisotopes				
RADIOISOTOPE	SYNMBOL	RADIATION	HALF-LIFE	USE
Tritium	$^{3}_{1}H$	β^-	12.33 years	Biochemical tracer
Carbon-14	$^{14}_{6}C$	β^-	5730 years	Archaelogical dating
Phosphorus-32	$^{32}_{15}P$	β^-	14.26 years	Leukemia therapy
Potassium-40	$^{40}_{19}K$	β^-	1.28×10^9 years	Geological dating
Cobalt-60	$^{60}_{27}Co$	β^-, γ	5.27 years	Cancer therapy
Technetium-99m*	$^{99m}_{43}Tc$	γ	6.01 hours	Brain scans
Iodine-123	$^{123}_{53}I$	γ	12.27 hours	Thyroid therapy
Uranium-235	$^{235}_{92}U$	α, γ	7.04×10^8 years	Nuclear reactors

**The m in technetium-99m stands for metastable, meaning that it undergoes gamma emission but does not change its mass number or atomic number.*

Radioisotopes have different half-lives. The more unstable, the quicker the decay! Learn more about half-live in this ***Radioactive Dating Game:*** *https://phet.colorado.edu/en/simulation/radioactive-dating-game.*

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