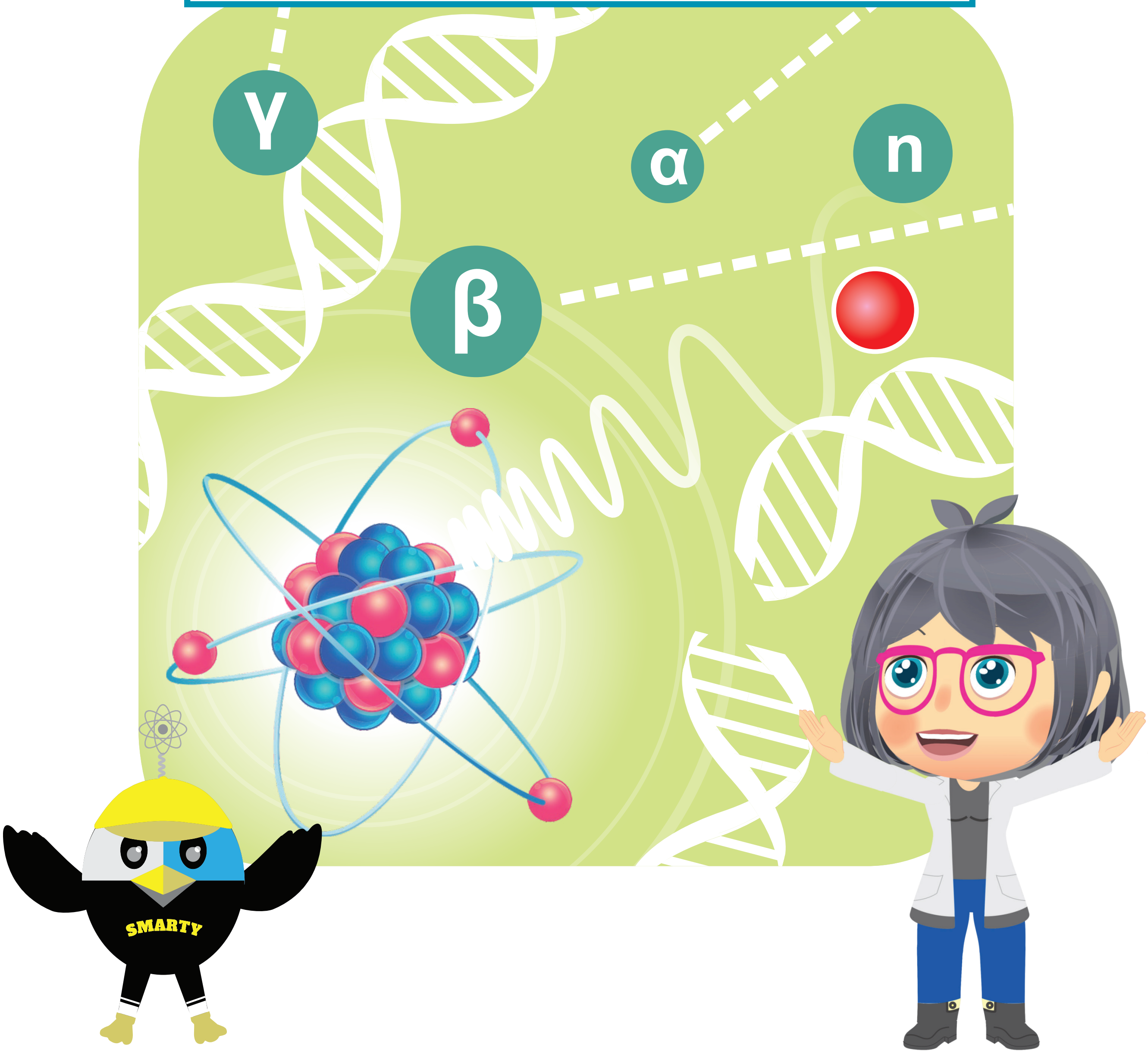
3 NUCLEAR 101

Ionizing Radiation and Matter



Nuclear 101

Ionizing Radiation and Matter

A Resource Material for Secondary Students and Science Teachers

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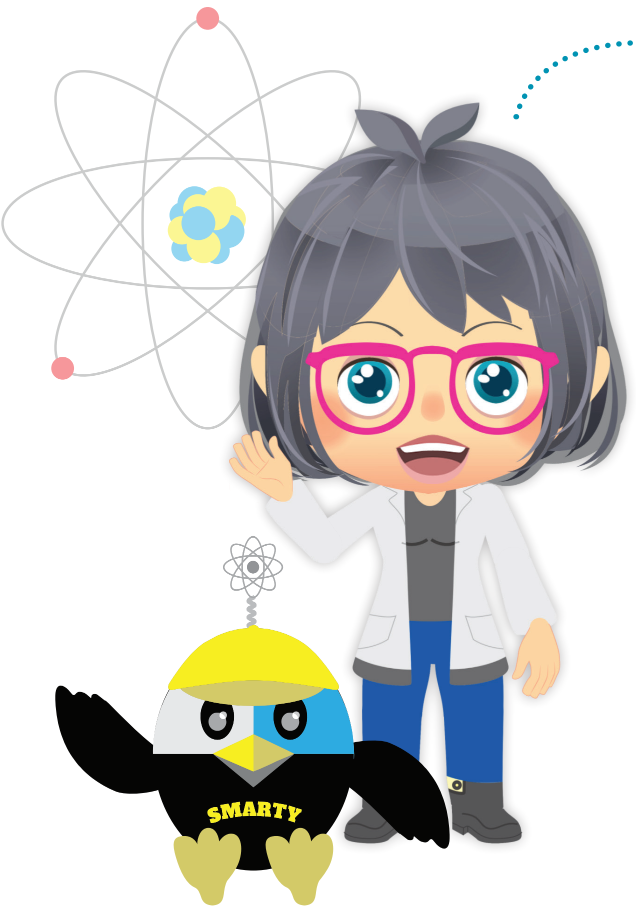
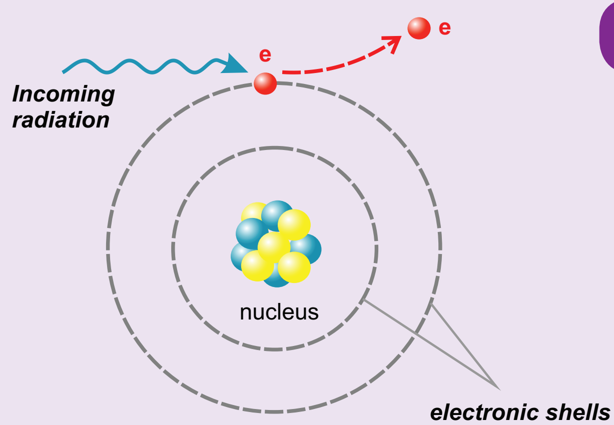


Hi there! I'm Radia! In this booklet, you will learn about:

1. *How radiation interacts with matter*
2. *The biological effects of ionizing radiation*
3. *Some ways to protect ourselves from ionizing radiation*

WHAT HAPPENS WHEN IONIZING RADIATION INTERACTS WITH MATTER?

Ionizing radiation, whether in the form of particles or waves, has enough energy to strip electrons from matter it interacts with. This is a process known as ionization. Alpha particles and beta particles are directly ionizing radiation while neutrons, gamma rays and x-rays are indirectly ionizing radiation.

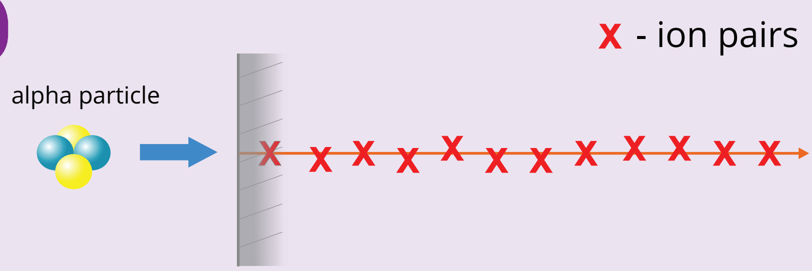


IONIZATION

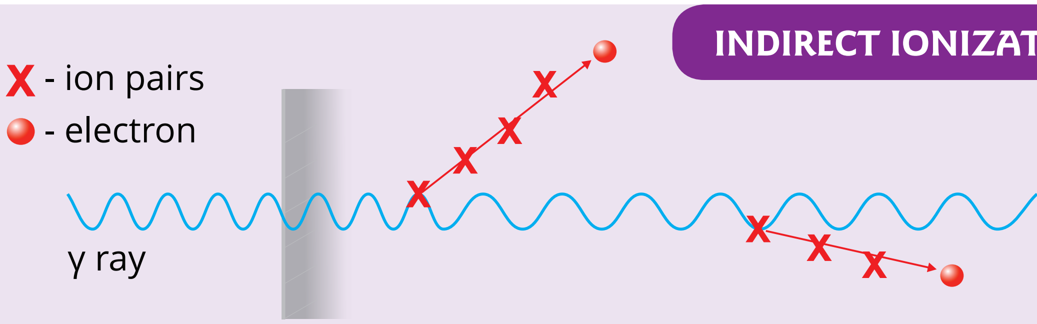
Ionizing radiation has enough energy to remove an orbital electron from the atom. This creates an ion pair -- the positively charged atom and the free electron.

DIRECT IONIZATION

Charged particles such as alpha and beta particles directly ionize atoms in the medium by exerting coulombic forces to push or pull electrons away from the atom.



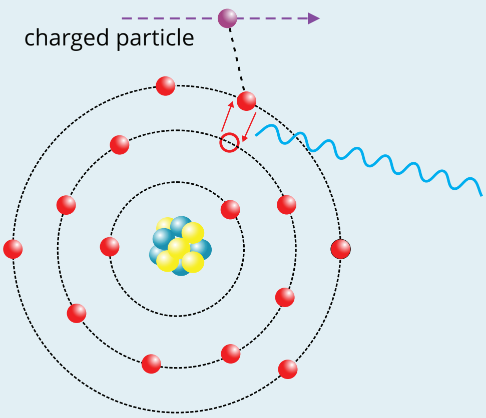
INDIRECT IONIZATION



Neutrons and photons such as gamma rays and x-rays ionize some atoms in the medium indirectly. First, when neutrons or photons interact with a material, it sets free a single electron through elastic scattering, Compton effect or photoelectric effect. Then, this energetic electron that is produced by the interaction goes on to produce other ionization events in nearby atoms. Hence, neutrons and photons largely rely on secondary electrons to cause actual ionizations.

Charged Particle Interactions

Charged particles like alpha particles and beta particles continuously interact with the electrons and nuclei of the surrounding atoms as they travel through matter. Because beta and alpha particles have charge, they interact with matter by virtue of electromagnetic forces and lose their kinetic energy through three principal mechanisms - (1) excitation, (2) ionization and (3) radiative losses.

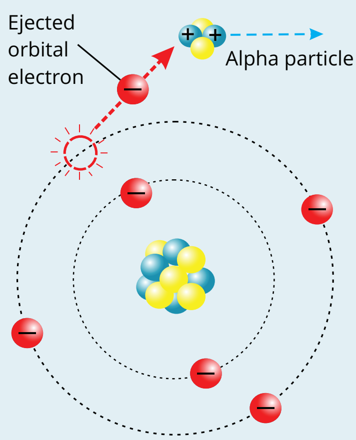


EXCITATION

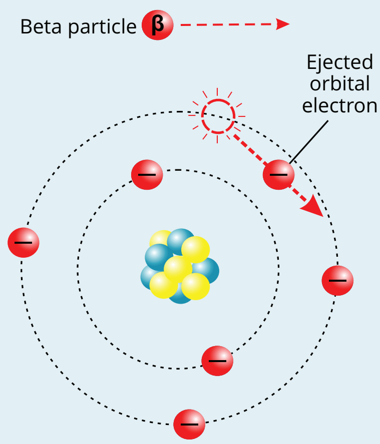
The charged particle exerts just enough force to promote one of the electrons in the atom to a higher energy state. The excited atom will then de-excite and emit a low energy photon.

IONIZATION

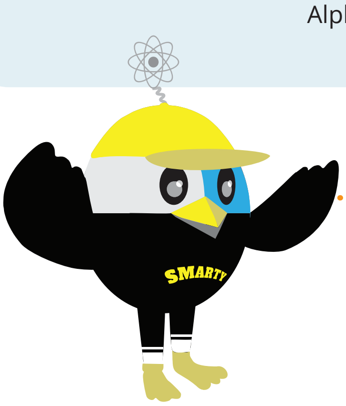
A charged particle exerts sufficient force to completely remove one or more electrons from the atom.



Alpha particles ionize by attracting an electron from an atom.



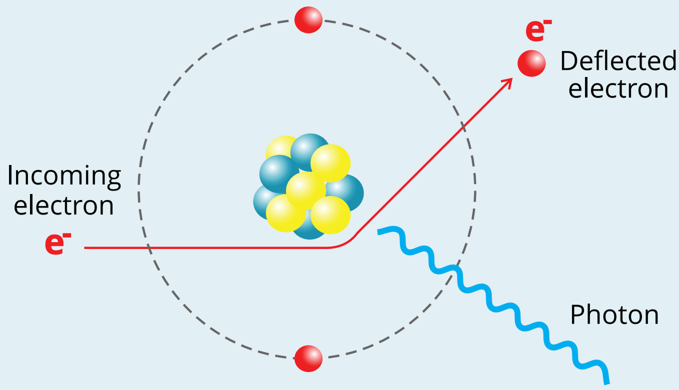
Beta particles ionize by repelling an electron from an atom.



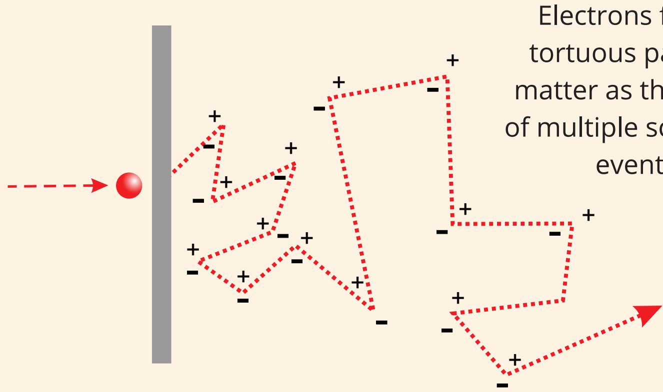
What do you think will happen to the alpha or the beta particles after they interact with the electrons in the atom? How about the ejected electrons, what do you think will happen to them?

RADIATIVE LOSS (BREMSSTRAHLUNG)

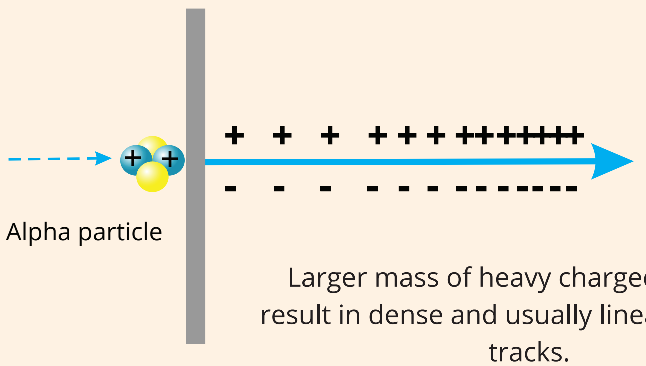
When charged particles are deflected or decelerated while traveling near the nucleus of an atom, bremsstrahlung x-rays are produced. Bremsstrahlung is almost exclusively associated with the deceleration of electrons because they are easily deflected due to their small mass. Large charged particles like alpha particles do not significantly produce bremsstrahlung x-rays.



Each ionization, excitation or radiative loss event reduces the velocity of the charged particle. In other words, alpha and beta particles slow down as they travel through matter. The average energy lost by a charged particle per unit distance travelled in a medium is called the linear energy transfer (LET).



Electrons follow tortuous paths in matter as the result of multiple scattering events



Larger mass of heavy charged particles result in dense and usually linear ionization tracks.

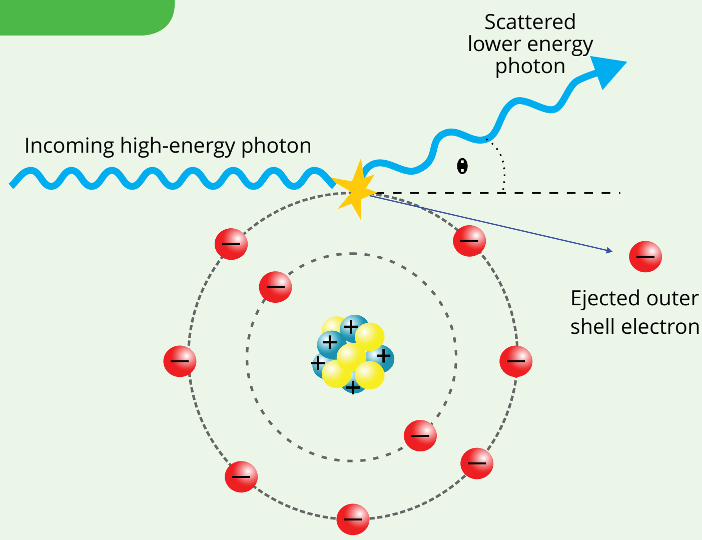
Alpha particles have higher LET and are more ionizing compared to beta particles. The high LET of alpha particles makes it easier to stop them, making shielding more effective and preventing deeper penetration into a medium. However, the concentration of deposited energy also causes more damage to the microstructures near the track of alpha particles.

Photon Interactions

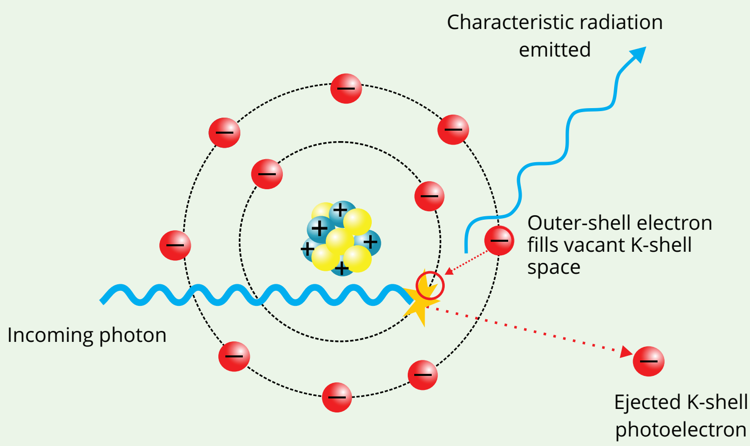
Ionizing radiation such as x-rays and gamma rays which are in the form of electromagnetic waves or photons, are either transmitted unchanged, scattered or absorbed when they interact with matter. Below are some of the scattering and/or absorption mechanisms involved. The prevalence of any of these interaction mechanisms depends on the energy of the x-rays or gamma rays and the atomic composition of the medium they pass through.

COMPTON SCATTERING

A photon interacts with an outer shell electron. Only some of the energy of the incident photon is imparted to the electron which results to a scattered photon that has lesser energy than that of the incident photon and an ejected electron.



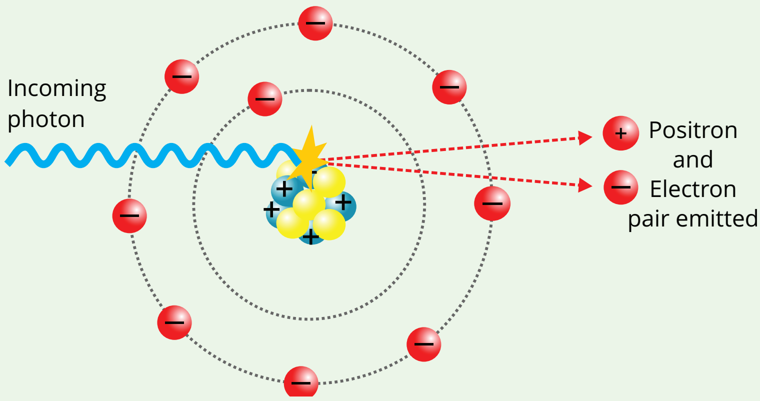
PHOTOELECTRIC EFFECT

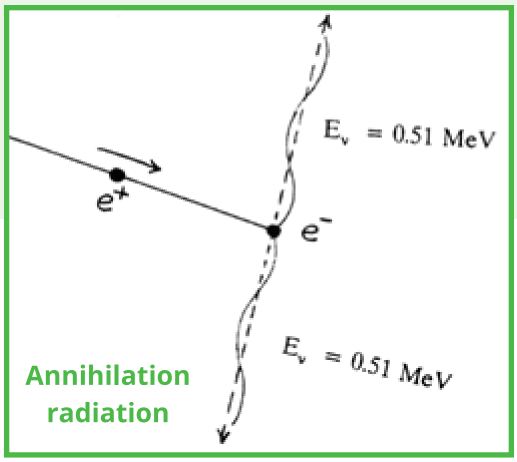


A photon interacts with an inner orbital electron such as a K-shell electron. All the energy of the incoming photon is transferred to and absorbed by the electron. If the absorbed energy is greater than the binding energy of the electron, the electron is ejected from the atom. After the electron is ejected, the vacancy in the atom can result in the emission of characteristic X-rays or Auger electrons.

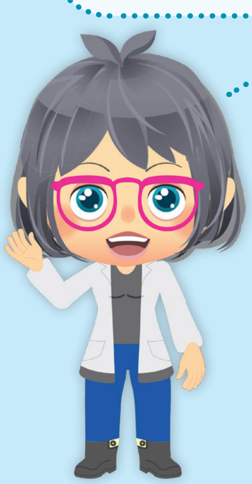
PAIR PRODUCTION

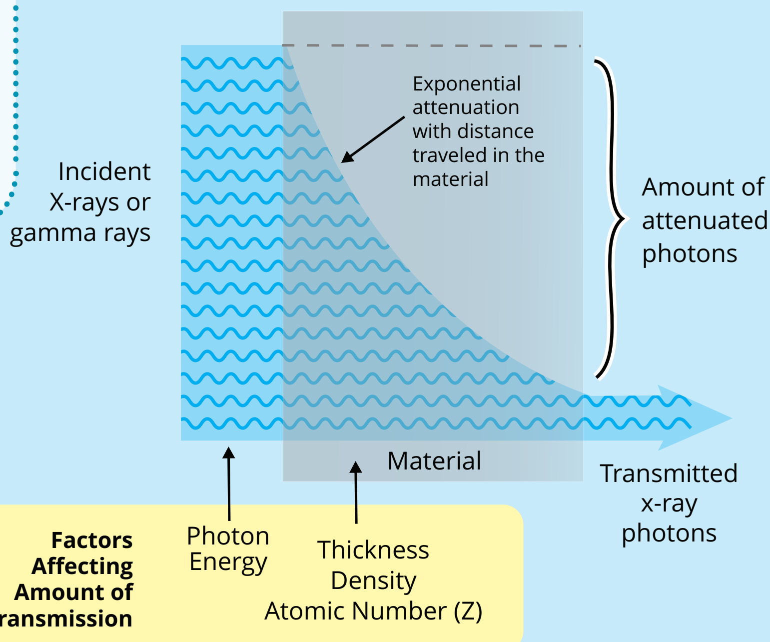
A photon is travelling with so much energy (greater than 1.02 MeV) and interacts with the nucleus of the atom. The photon energy is then converted into an electron-positron pair. After pair production, the electron wanders off and interacts with nearby atoms while the positron quickly reacts with another electron by annihilation! The resulting mutual annihilation sends two 0.511 MeV photons moving in opposite directions. It's an amazing example of Einstein's mass-energy equivalence!





"Due to the combined effect of scattering and absorption, the intensity of x-rays and gamma rays is reduced as they passed through matter. This reduction of intensity is called attenuation. The amount of attenuated photons depends on the photon energy and the property of the medium like thickness, density and atomic number."

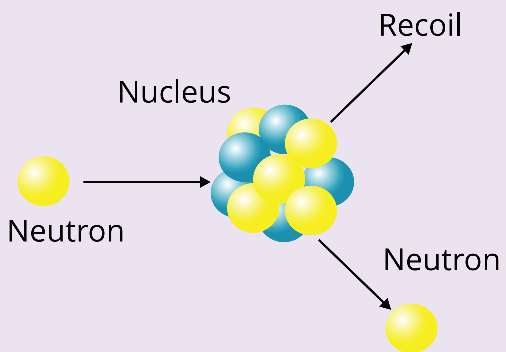




Neutron Interactions

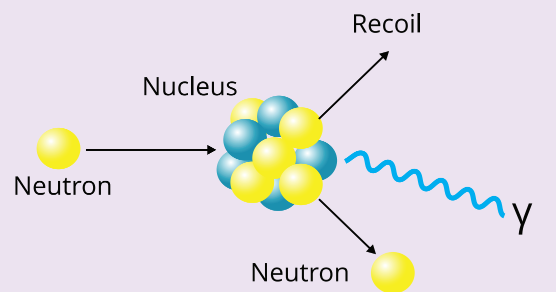
Neutrons are uncharged particles. They do not interact with the electrons in the atom. Like billiard balls colliding with one another or billiard balls colliding with pingpong balls, a neutron will cause changes in the atom it interacts with depending on how fast or how slow it moves towards the nucleus of the atom. Slow neutrons can be scattered elastically or inelastically or "captured" by the nucleus of the atom while fast neutrons, when not scattered, can impact the nucleus, liberating charged particles or nuclear fragments.

ELASTIC SCATTERING



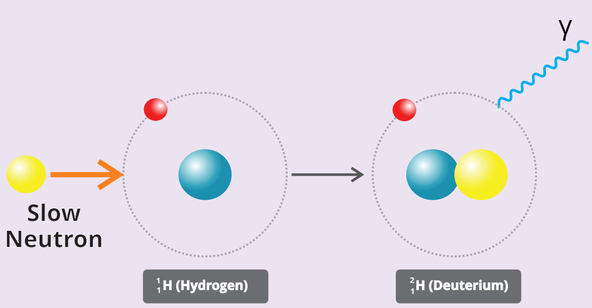
A neutron is scattered in a collision with an atomic nucleus similar to billiard balls colliding with one another. The nucleus recoils and loses energy by excitation. No gamma rays are emitted by the nucleus after collision.

INELASTIC SCATTERING



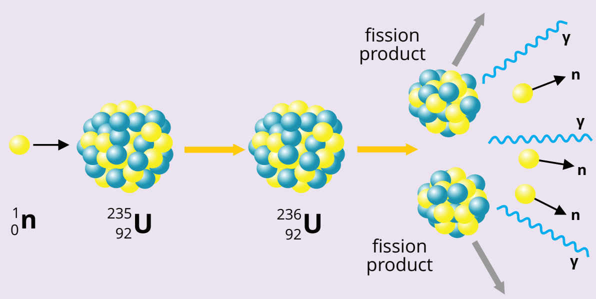
A neutron collides with a large atomic nucleus and is scattered in a collision much like how a pingpong ball strikes a billiard ball. Because the collision is inelastic, the neutron transfers some energy to the nucleus after collision. This causes the nucleus to be "excited" and releases gamma rays.

NEUTRON CAPTURE



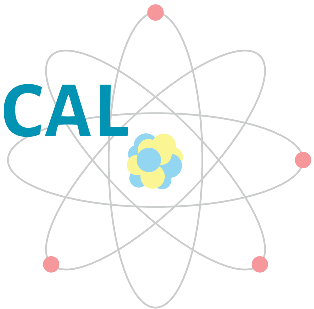
Neutrons can be "captured" into a nucleus and interact with the internal nuclear forces such that the atom becomes a completely different atom after emitting radiation such as gamma rays or charged particles.

FISSION



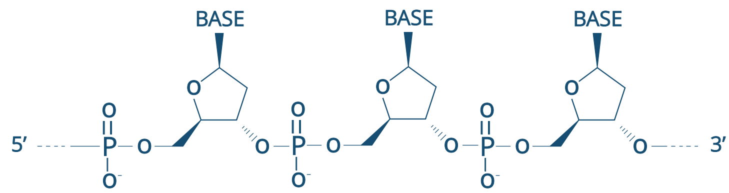
Neutrons that directly hit a larger nucleus can split the atom, producing energy and releasing more neutrons, other nuclear fragments and gamma rays.

WHAT ARE THE BIOLOGICAL EFFECTS OF IONIZING RADIATION?

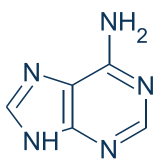


Whether the source of radiation is natural or man-made, small dose or large dose, there will be some biological effects that results from exposure to radiation. Biological effects begin with the consequence of radiation interactions with the atoms forming the cells, especially the DNA.

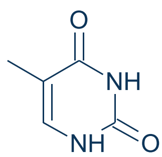
THE SUGAR PHOSPHATE 'BACKBONE'



DNA is a polymer made up of units called nucleotides. Each nucleotide is made of three different components: a sugar group, a phosphate group, and a base. Thee are four different bases: adenine, thymine, guanine, and cytosine.

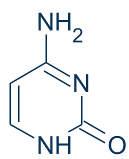


Adenine



Thymine

Guanine



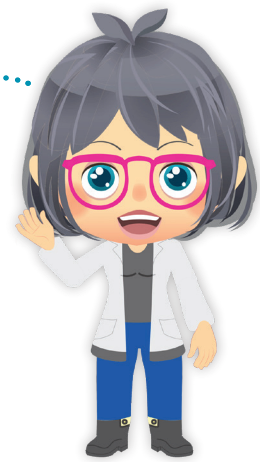
Cytosine

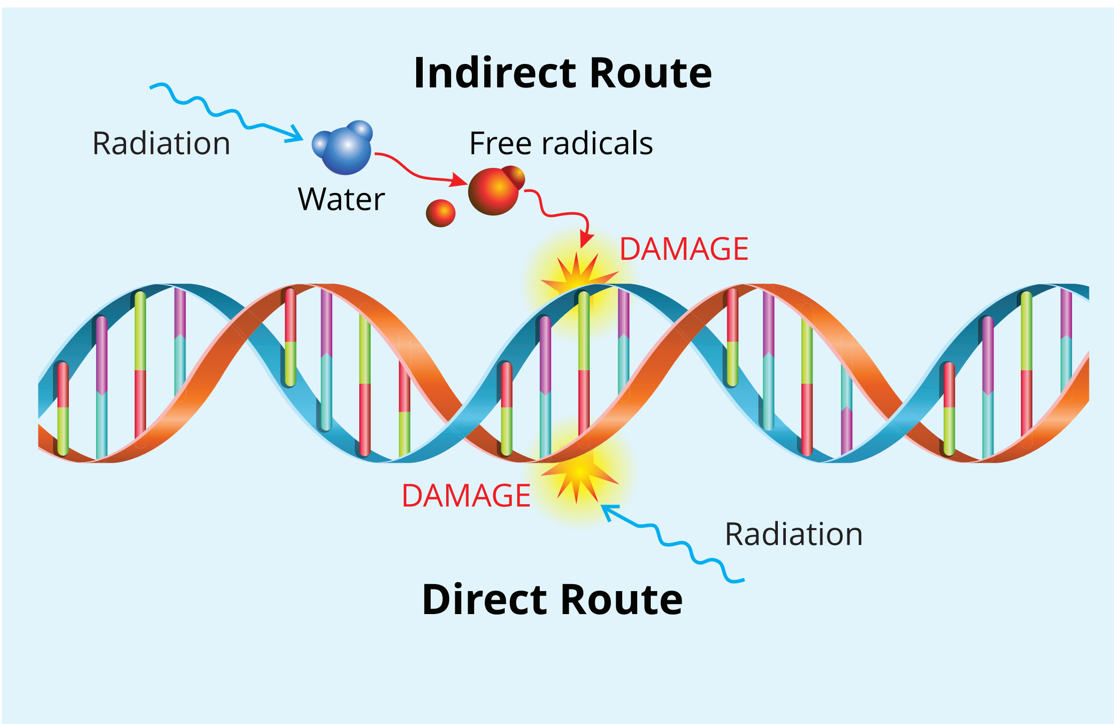
DNA is a very long molecule that stores our genetic information. It lies curled up inside the nucleus of a cell. It is made up of two strands, which spiral around each other in a double helix shape. Each strand of DNA is made up of a chain of nucleotides. These nucleotides are composed of a sugar phosphate and nitrogenous base – adenine (A), thymine (T), guanine (G) and cytosine (C). These bases link together and form base pairs through hydrogen bonding. Adenine always pairs with thymine via two hydrogen bonds. Cytosine pairs with guanine via three hydrogen bonds.

Direct and Indirect Effect to Cells

There are two mechanisms by which radiation affects cells – direct and indirect effects. If a cell is exposed to radiation, the probability of direct interaction with the DNA molecule is very small since these components make up such a very small part of the cell. However, just like the human body, each cell, is mostly water. When radiation interacts with water, it may break the bonds that hold the water molecules together, resulting to a production of "free radicals" such as hydrogen (H*) and hydroxyls (OH*). These free radicals may recombine or may interact with other ions in the cell to form compounds which could harm the cell. This is an indirect effect of radiation to cells.

There are two main ways radiation can affect the DNA in cells. Radiation can strike the DNA molecule directly, ionizing and damaging it. Alternately, radiation can ionize water molecules, producing free radicals that react with and damage DNA molecules.

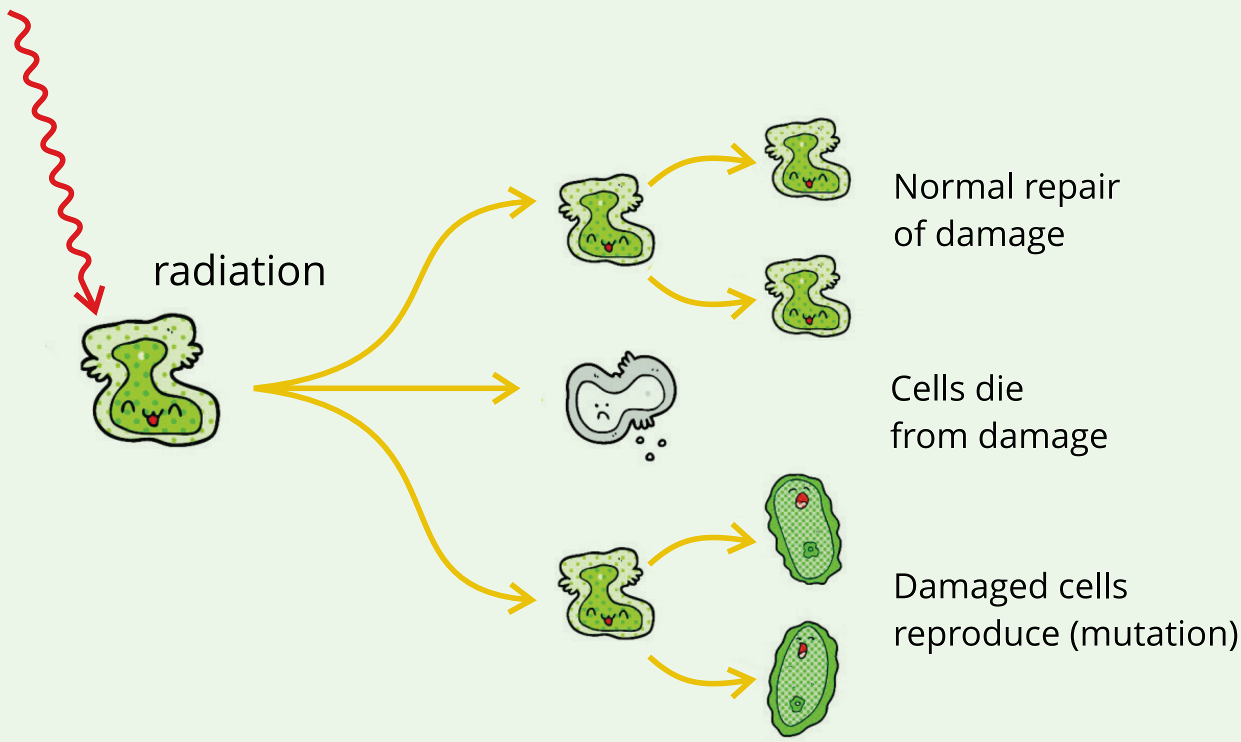




Cell response to radiation effects

The human body has a tremendous ability to repair damage coming from various elements, including radiation. As a result, not all effects and damages to cells are irreversible. In many instances, the cells can completely repair the damage and function normally. If the damage is severe enough, the affected cells die. This usually happens at exposures to high doses of radiation. Another possible result is that the cell is affected in such a way that it does not die but simply mutates. The cell with mutations in its DNA may then reproduce, perpetuating the mutation, which could be a beginning of some types of tumor.

WHAT HAPPENS AFTER RADIATION INTERACTS WITH CELLS?



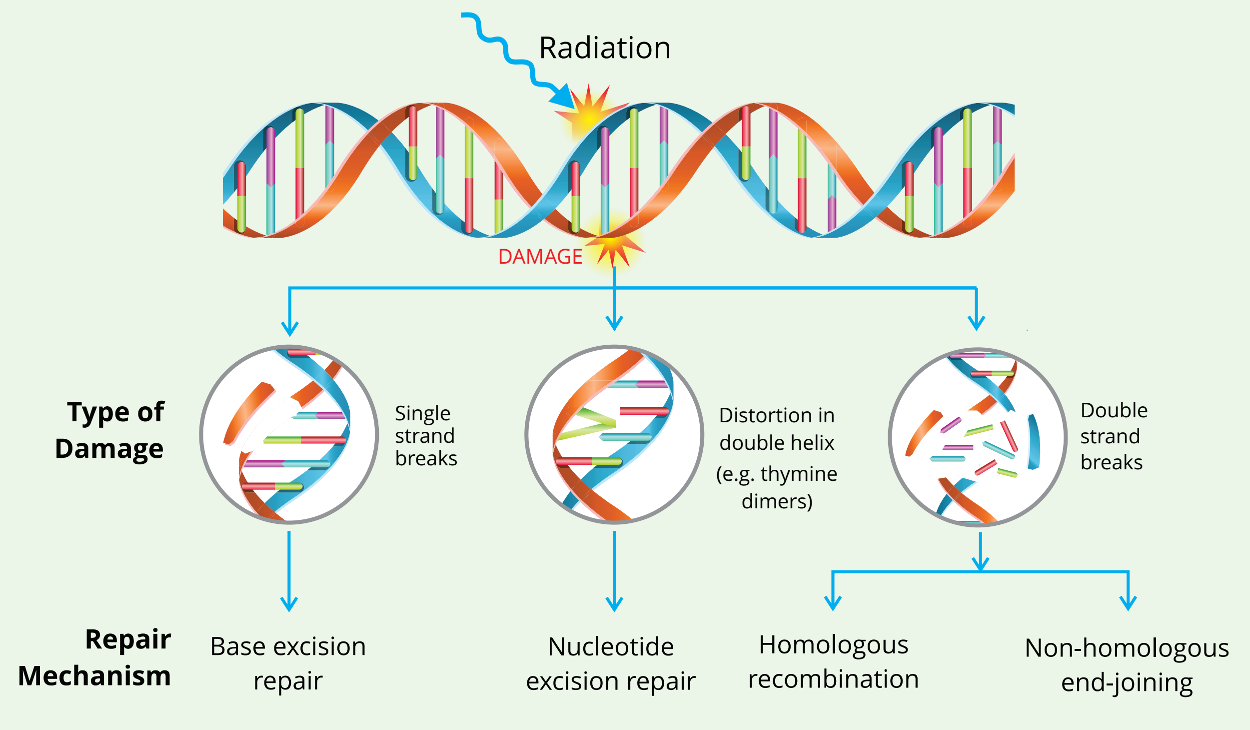
MISCONCEPTION ALERT!

The cell itself does not mutate. It is the genetic information that is changed due to the mutation in DNA. Mutations could lead to a loss or a gain of functions of genes which is manifested by a different observable characteristic or phenotype.

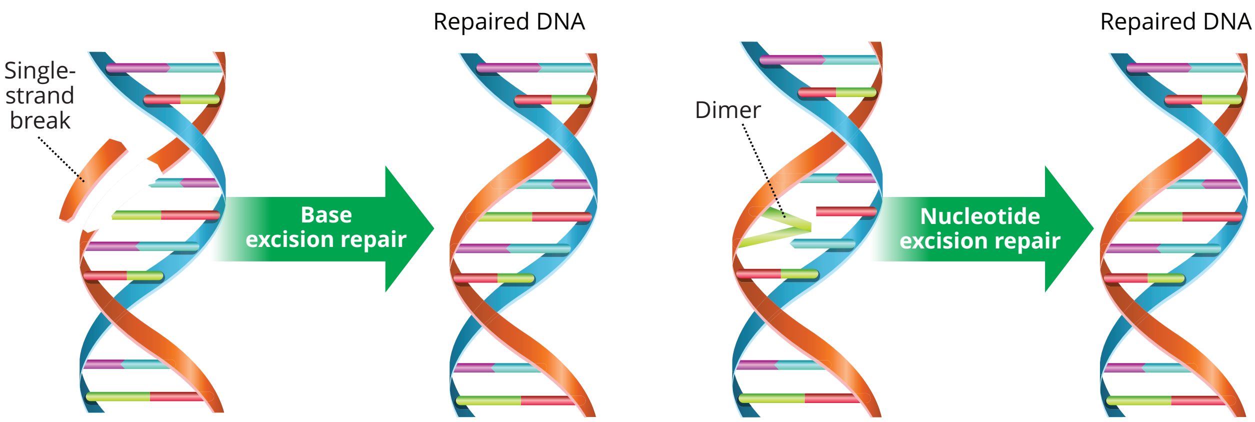
Cell repair mechanisms

The human body has various mechanisms for finding and repairing damaged DNA before it gets out of control. This repair pathways involve different types of specialized enzymes, depending on the kind of damage radiation has done to the DNA.

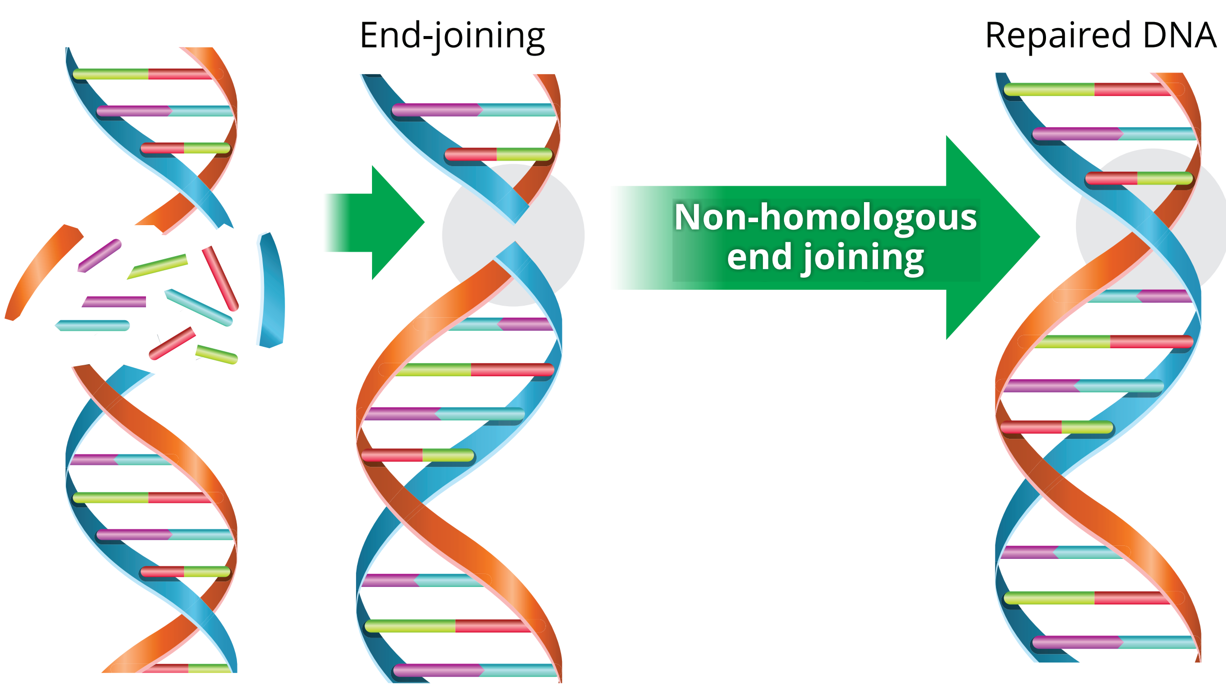
BASIC DNA REPAIR PATHWAYS

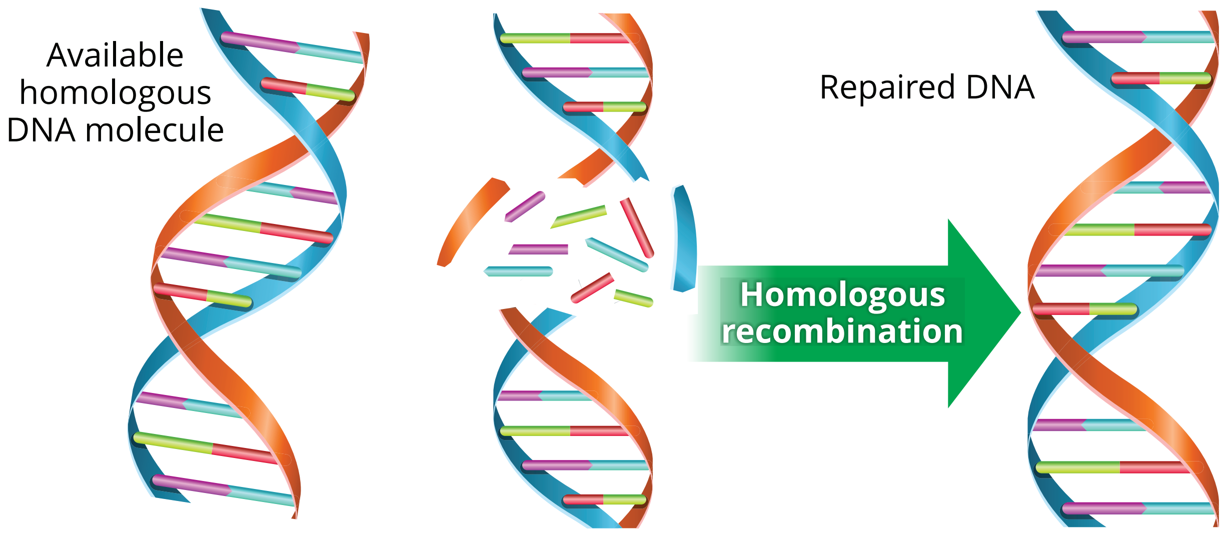


Single strand breaks are repaired by using the other complimentary strand as template to guide the repair process. If only one nucleotide base is damaged, it can be fixed by a process called base excision repair where the damaged base is snipped out and replaced with a new one. Radiation can also damage DNA by forming dimers that distort the DNA’s double helix shape. In this case, two adjacent thymine nucleotides or two adjacent cytosine nucleotides incorrectly bond with each other. Nucleotides are meant to bond with their complementary pair – that is, cytosine is meant to bond with guanine and thymine is meant to bond with adenine. When this kind of damage happens, the whole section of the nucleotide is cut out and replaced. This process is called nucleotide excision repair.



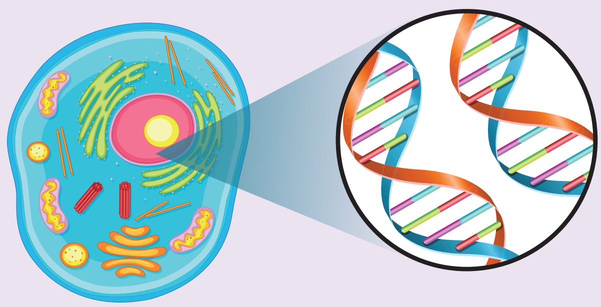
Double strand breaks can also occur especially when high energy radiation interacts with the cells. Double strand breaks are more difficult to repair. There are two types of repair mechanisms for double strand breaks – homologous recombination and non-homologous end joining. In homologous recombination, an identical or highly similar DNA molecule is around that matches the damaged one. This DNA molecule is then used as a template to repair the break. If there is no identical DNA molecule available at the time of radiation damage, then the two broken ends are fused back together in a process known as non-homologous end joining. Because non-homologous end joining is not totally accurate and can involve the loss or addition of nucleotides at the damaged site, it tends to produce a mutation.





Did you know that our bodies have genes that protects us against cancer? These genes are called tumor suppressor genes. Tumor suppressor genes encode proteins that stop cancerous cells from proliferating!

NORMAL CELL



CANCER CELL

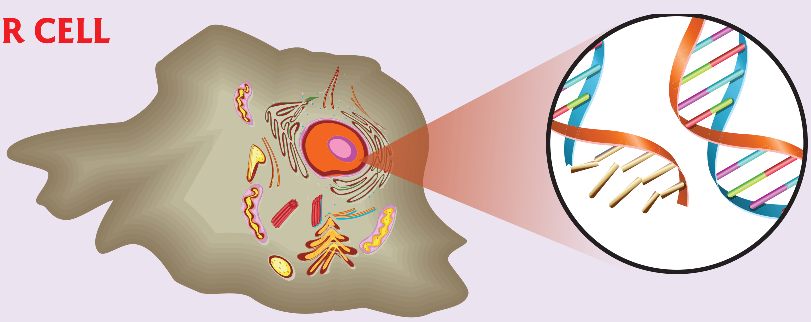


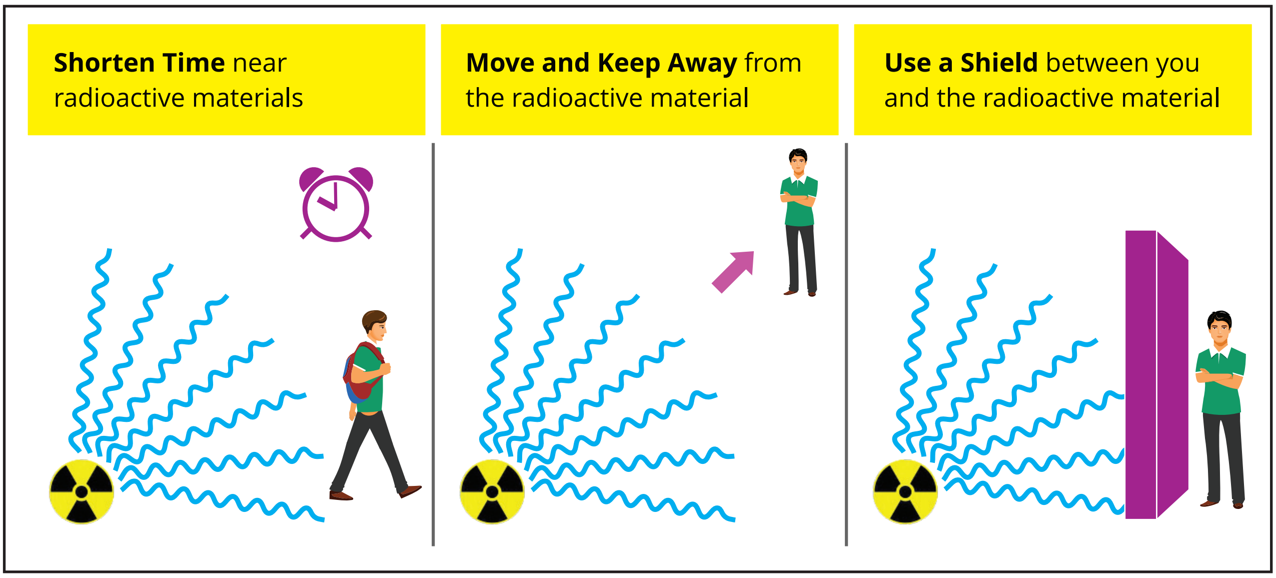
Image reference: https://visualsonline.cancer.gov/details.cfm?imageid=12495

HOW DO WE PROTECT OURSELVES FROM IONIZING RADIATION?

We cannot avoid ionizing radiation that occurs naturally. However, there are some things we can do to reduce our exposure to man-made sources. Additionally, government regulations following recommendations of safety standards such as those provided by the International Commission on Radiological Protection (ICRP) are in place to protect human health and the environment.

Principles of Radiation Safety

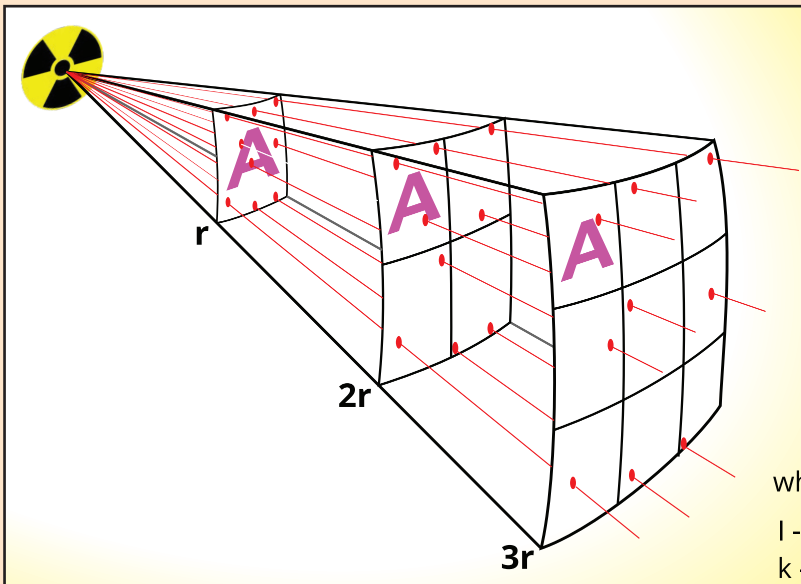
Time, distance and shielding are primary principles to which reduction of external exposure to radiation are based upon:



TIME: Spend less time near radioactive materials. Exposure doses to ionizing radiation decreases as the time spent near the source shortens.

Total dose = (Dose Rate) x (Time of Exposure)

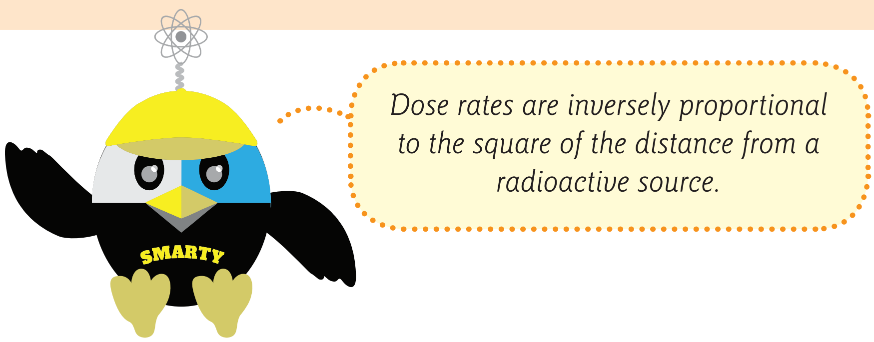
DISTANCE: Move or keep away from a radioactive material. Exposure doses decrease as the distance from the source increases.



$$I = \frac{k}{r^2}$$

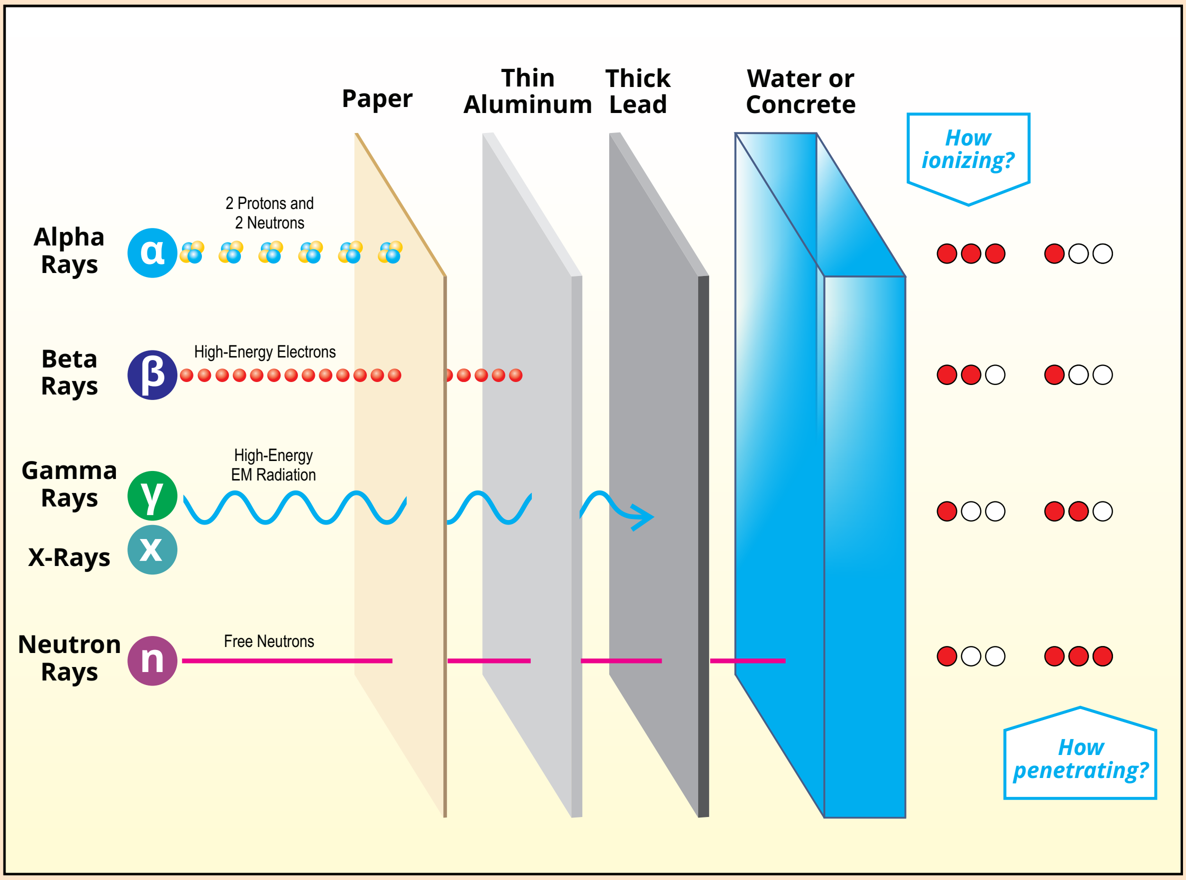
where:

I - intensity of radiation
k - proportionality constant
r - distance from source



Understanding how the different types of radiation interact with matter is essential in order to determine appropriate shielding requirements as well as in providing appropriate radiation protection measures.

SHIELDING: Inserting a proper shield between you and a radioactive material will greatly reduce or eliminate the exposure dose you will otherwise receive. For instance, using lead, thick concrete, or large amounts of water as a barrier provides protection from highly penetrating gamma rays.



Do you think it's a good idea to use lead as shielding material for beta particles? To minimize the production of unwanted bremsstrahlung radiation, beta sources should be shielded with a low atomic number material.

Basic Principles of Radiation Protection

In 1928, the International X-ray and Radium Protection Committee was established for the purpose of protecting healthcare workers from radiation hazards. In 1950, the Committee was reorganized into the International Commission on Radiological Protection (ICRP), which was assigned a significant role as an international organization that makes recommendations concerning basic frameworks for radiological protection and protection standards. To date, the Commission made recommendations to a system of radiological protection in 1977, 1990 and in 2007. When the ICRP releases its recommendations, many countries review their laws and regulations on radiological protection accordingly.

People's exposure to ionizing radiation is classified as either planned, existing or emergency. The ICRP's recommendations applies to planned, emergency, and existing exposure situations and can be summed up in three general principles – (1) justification; (2) optimization and (3) dose limitation. The principle of justification and optimization are source-related and applies to all exposure situations while the principle of dose limitation applies is individual-related and only applies to planned exposures.

Exposure Situations and Protection Measures

Planned exposure situations	Existing exposure situations	Emergency exposure situations
Situations where protection measures can be planned in advance and the level and range of exposure can be reasonably forecast	Situations where exposure has already occurred as of the time when a decision or control is made.	Contingency situations where urgent and long-term protection measures may be required.
DOSE LIMITS (Public exposure) 1 mSv/year (Occupational exposure) 20 mSv/year	**REFERENCE LEVEL** A lower dose range within 1 to 20 mSv/year, with a long-term goal of 1 mSv/year	**REFERENCE LEVEL** Within 20 to 100 mSv/year
MEASURES Manage disposal of radioactive waste and long-lived radioactive waste	**MEASURES** Ensure voluntary efforts for radiological protection and cultivate a culture for raiological protection	**MEASURES** Evacuate, shelter indoors, analyze and ascertain radiologcal situations, prepare monitoring, conduct health examinations, manage foods, etc.

mSv = millisieverts

Source: ICRP Publication 1013, "The 2007 Recommendations of the International Commission on Radiologial Protection" (ICRP, 2007)

JUSTIFICATION: Any decision that alters the radiation exposure situation should do more good than harm.

✓ Adopt

✗ Do not adopt

OPTIMIZATION: Doses should all be kept as low as reasonably achievable.

ALARA

A s
L ow
A s
R easonably
A chievable

ALARA stands for "as low as reasonably achievable". This principle means that even if it is a small dose, if receiving that dose has no direct benefit, you should try to avoid it.

DOSE LIMITATION: The total dose to any individual should not exceed the appropriate limits.

Type of limit	Occupational	Public
Effective dose	20 mSv/year, averaged over defined periods of 5 years	1 mSv/year
Annual equivalent dose in		
Lens of the eye	150 mSv	15 mSv
Skin	500 mSv	50 mSv
Hands and feet	500 mSv	--

mSv millisievert, 1 sievert is equal to 100 roentgen equivalent in man (rem)

EXCEPTION: Dose Limits are NOT applied to medical exposure.

Notes

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