

The background features a dark blue field with several large, semi-transparent gears of varying shades of blue. On the left side, there is a vertical strip with a colorful, textured appearance, resembling a particle detector strip or a microscopic image, with colors ranging from orange to purple.

# Nuclear physics basics

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# Contents

## **Atomic nucleus**

- ✦ Atom is made of nucleus and electron cloud
- ✦ Atom doesn't behave as macroscopic objects
- ✦ Atomic nucleus: hidden part of an atom
- ✦ Isotopes: variants of the same element

# ★ Radioactive nuclei

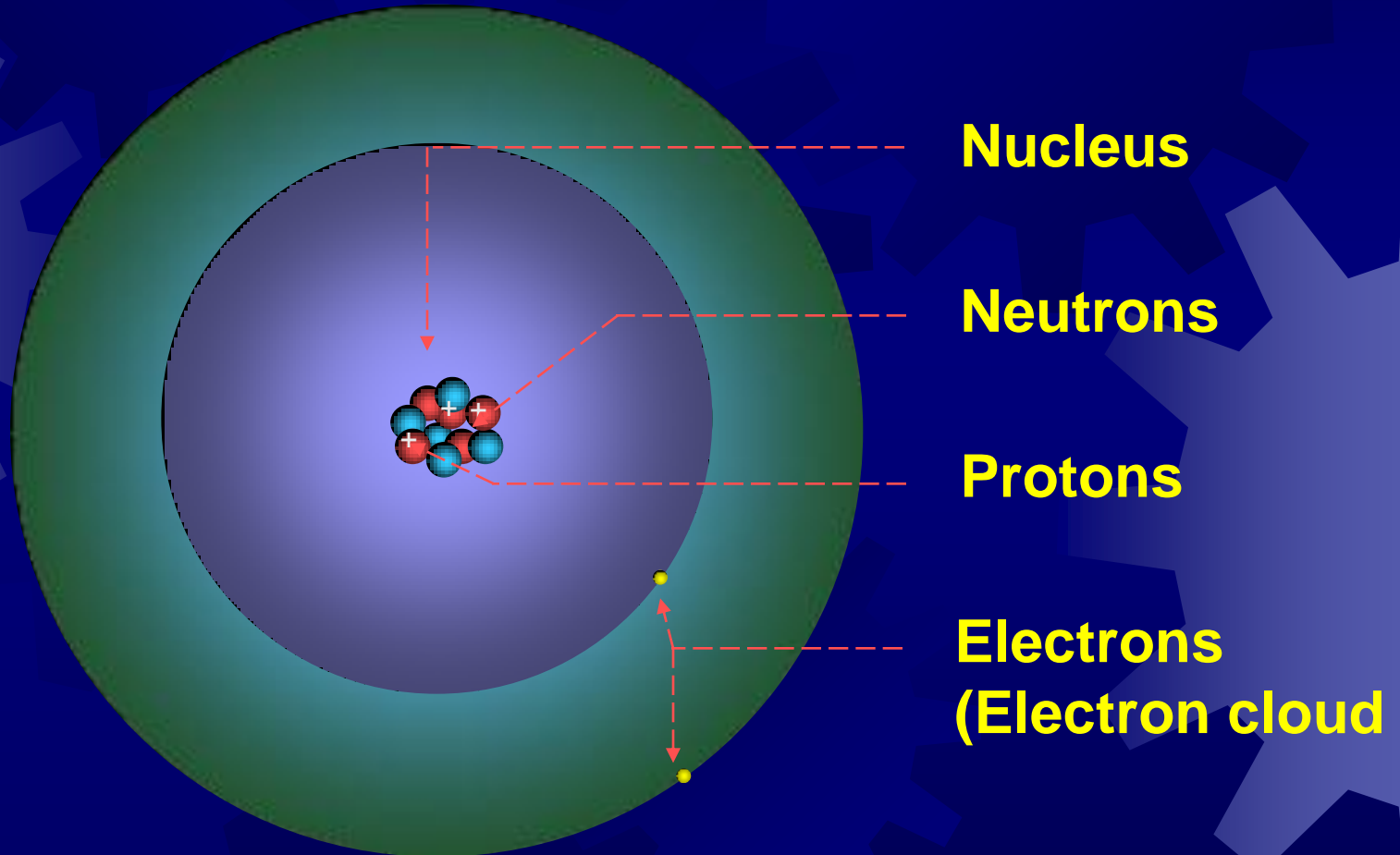
- ★ Stable nuclei have balanced numbers of protons and neutrons
- ★ Radioisotopes have unstable nuclei
- ★ Majority of radioisotopes are artificial
- ★ Unstable nucleus undergoes violent changes
- ★ Alpha decay: heavy unstable nucleus rejects helium nucleus
- ★ In beta decay some particles disappear and others are created
- ★ By gamma decay nucleus disposes excess energy
- ★ Radioactive nuclei die without getting old



# Atomic nucleus

- ✦ ATOM CONSISTS OF NUCLEUS AND ELECTRON CLOUD

# Atomic structure



# Nucleus :

- ✦ Positioned in atom center
- ✦ Occupies negligible volume
- ✦ Mass: 99.9% of atom
- ✦ Protons + Neutrons = Nucleons
- ✦ Atomic number:  $Z$  (# of protons/electrons)
- ✦ Mass number:  $A = Z + N$ ;  $N$  is # of neutrons

# Forces

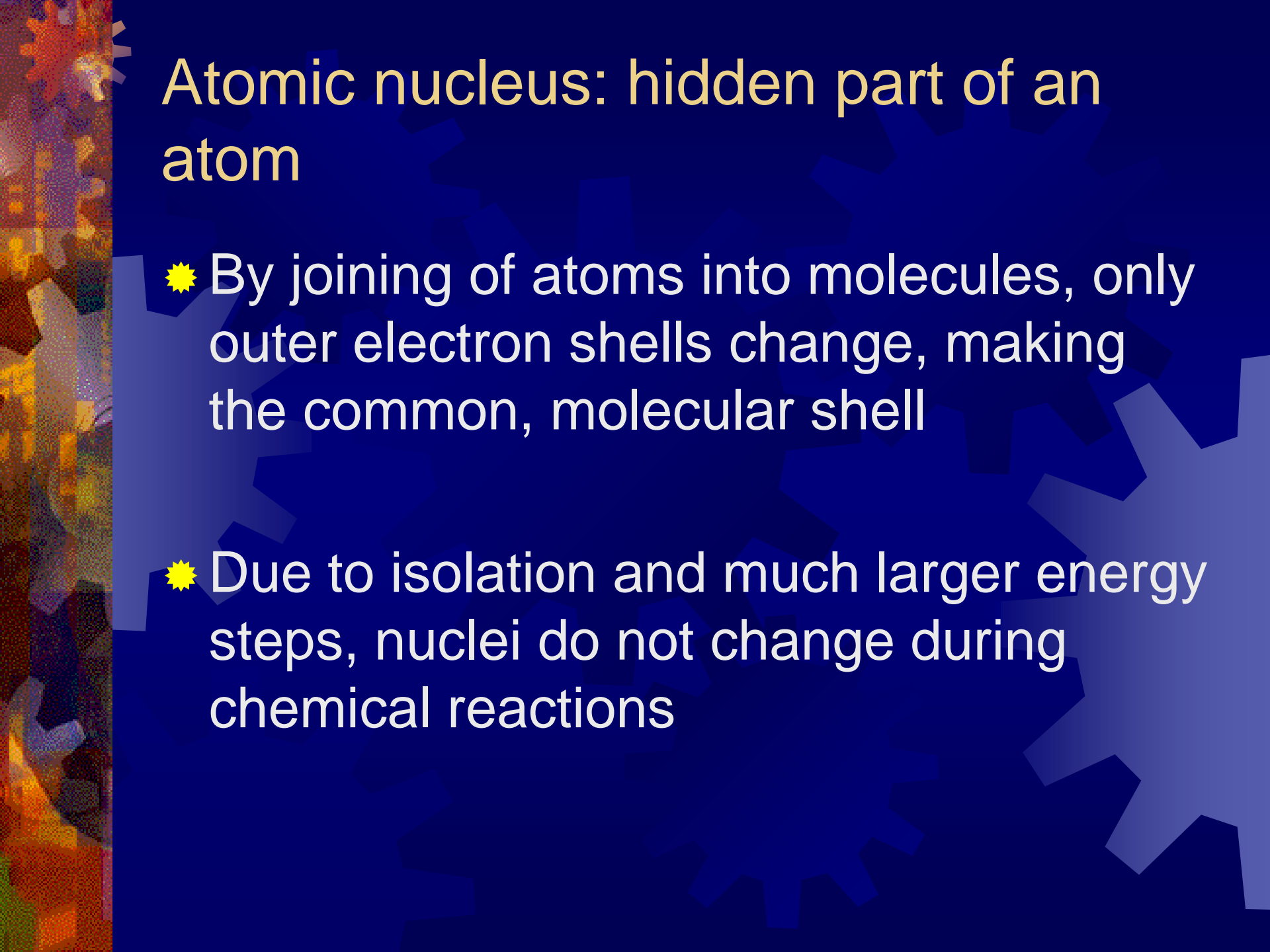
- ✦ **Coulomb force** gathers electrons around nucleus
- ✦ **Nuclear (strong) force** assembles nucleons, overpowering the repulsive Coulomb force between protons; it has short range



# Atom acts differently than macroscopic objects

- ✦ Naive conception – Solar system
- ✦ Quantum physics – discretization of energy levels: electrons and nucleons can fill in only the given, mutually separated energy levels



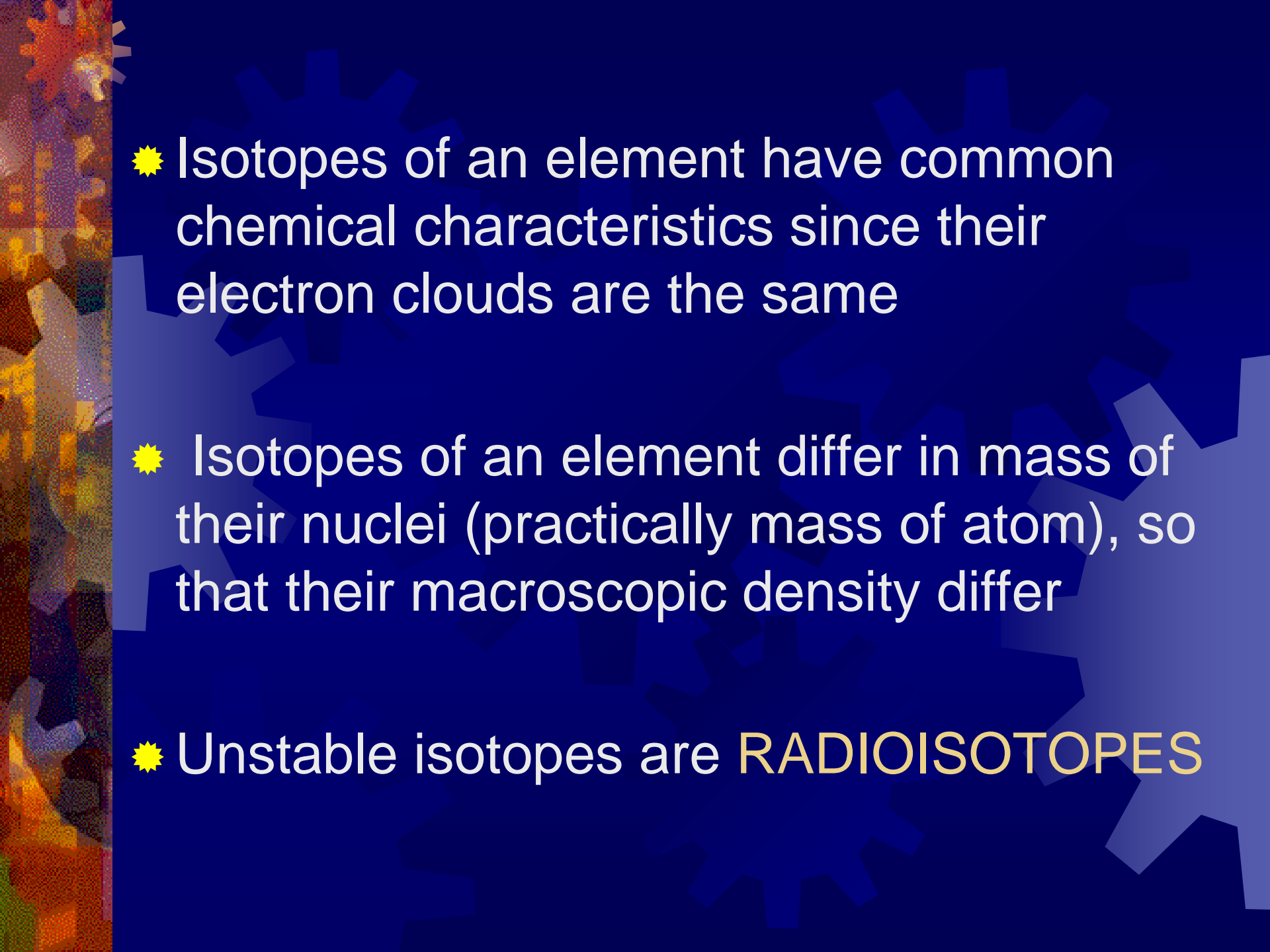


# Atomic nucleus: hidden part of an atom

- ✦ By joining of atoms into molecules, only outer electron shells change, making the common, molecular shell
- ✦ Due to isolation and much larger energy steps, nuclei do not change during chemical reactions

# Isotopes – variants of the same element

- ✦ Atom of an element  $X$  is denoted as  $X-A$ , and its nucleus as  ${}_Z^AX$ , where  $X$  is an element symbol;  $Z$  and  $A$  are atomic and mass numbers, respectively
- ✦ Atoms having equal  $Z$  and different  $N$  are different **isotopes** of the same chemical element

- 
- ✦ Isotopes of an element have common chemical characteristics since their electron clouds are the same
  - ✦ Isotopes of an element differ in mass of their nuclei (practically mass of atom), so that their macroscopic density differ
  - ✦ Unstable isotopes are **RADIOISOTOPES**



☀ Isotopes of *different* elements are called  
NUCLIDES

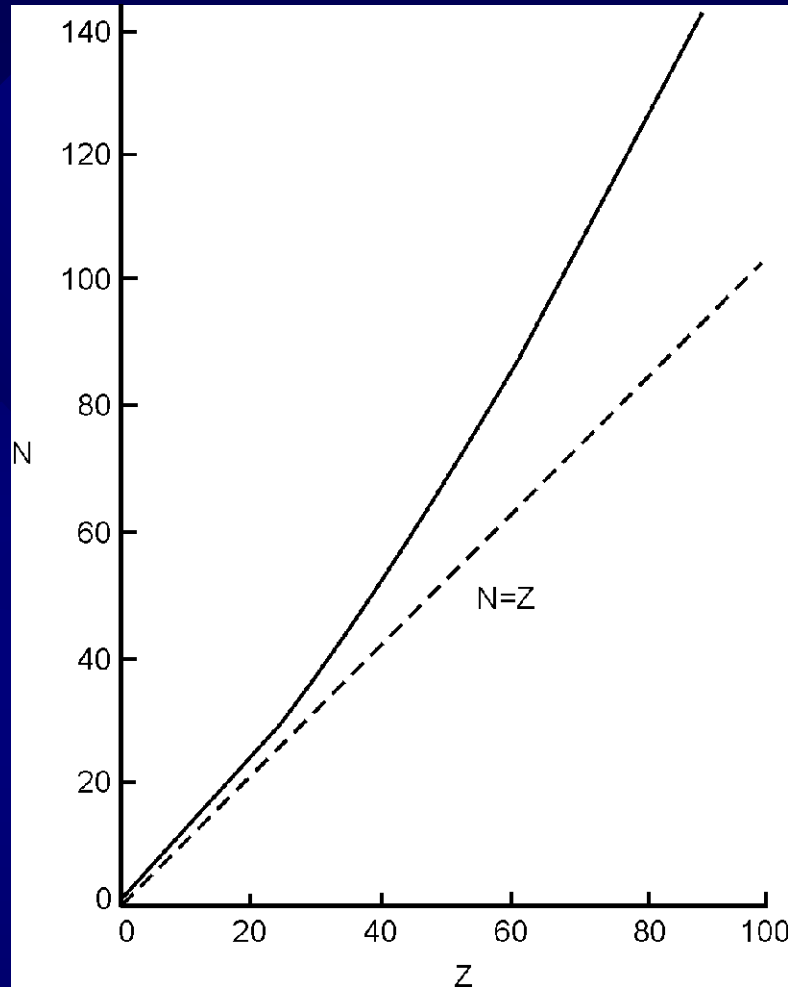
☀ Unstable nuclides are RADIONUCLIDES



# Radioactive decays

# Stable nucleus = matched numbers of protons and neutrons

- ★ Nuclear force dominates over repulsive electric force only at small distances between neighboring protons; more distanced protons only 'feel' repulsion.
- ★ Neutrons attract both protons and neutrons, stabilizing the nucleus
- ★ Condition of stability:  $N > Z$



## Relationship N vs. Z

Stable nuclei are in the narrow region around full line

# Radioisotopes have unstable nuclei

- ✦ Unfavorable N/Z ratio => radioactive decay (unstable isotope)





Majority of radioisotopes is artificial

Production:

-NUCLEAR REACTORS

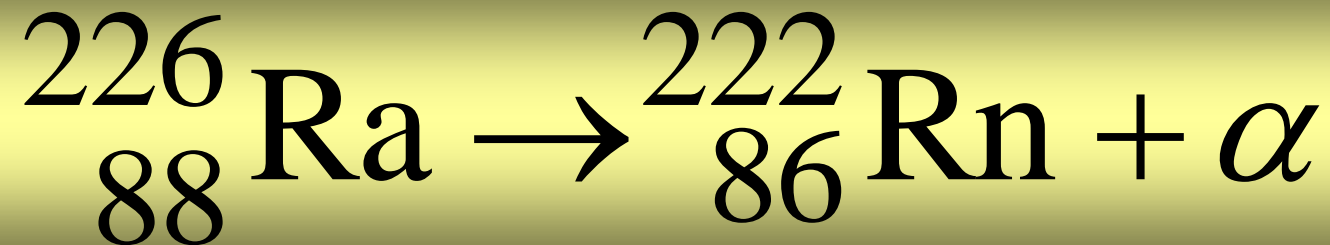
-PARTICLE ACCELERATORS

# Radioactive decay

- ✦ Spontaneous transformation of nucleus in one or several steps in order to achieve stable energetic states
- ✦ Particles and photons emitted are **RADIOACTIVE RADIATION**

## Alpha decay

- ★ Heavy unstable nucleus rejects helium nucleus: alpha particle

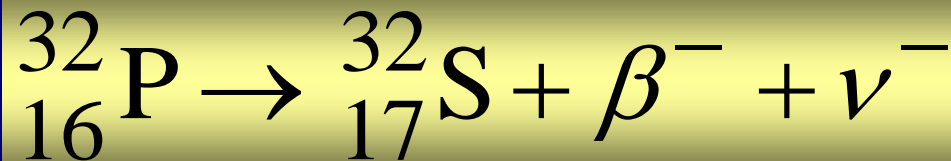


$$E_k = 4.8 \text{ MeV}$$

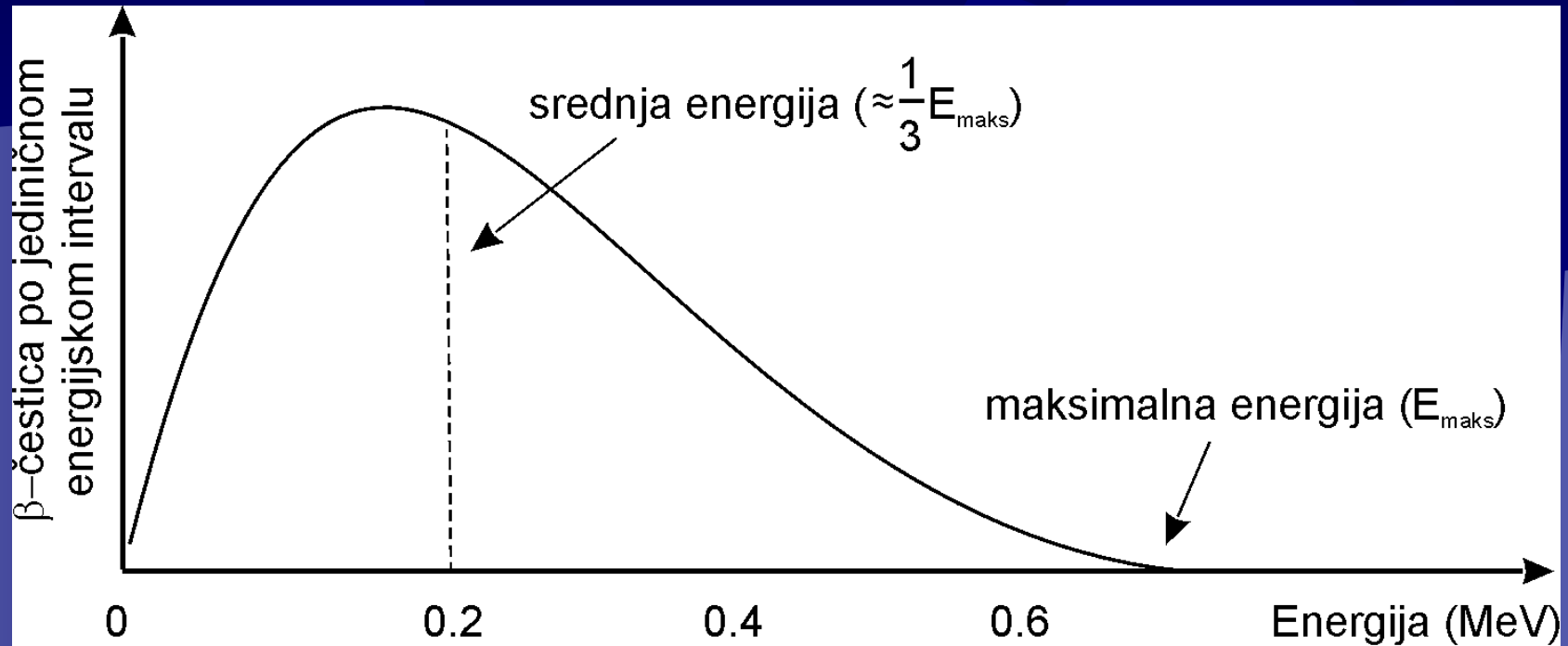
# Beta decay (s)

- ★ Some particles are created, others disappear

- ★  **$\beta^-$  decay:** transformation of neutron into proton - produces fast electron and antineutrino:



- ★  **$\beta^+$  (positron decay):** transformation of proton into neutron- produces fast positron and neutrino, which is followed by: **ANIHILATION RADIATION:** collision of electron and positron- both disappear on account of 2 photons of 511 keV



Beta-plus energy spectrum of Cu-64



**Beta decays** -> elementary particles can transform one into another.

The transformation of nucleons (proton into neutron and vice versa) in beta-decay is caused by **weak force**

Weak force acts between particles called leptons (electron, neutrino and their antiparticles are leptons).

The transformation of nucleons, mediated by weak force, is always accompanied by emission of two leptons, which are particle-antiparticle pair.

# Gamma decay – nucleus gets rid of excess energy

- ★ After alpha or beta decay the daughter nucleus most often is not in its energy ground state, but in one of excited states
- ★ By lowering to ground state (in one or several steps), the gamma photon (s) is emitted => **GAMMA DECAY**

**Gamma decay does not produce new element !!!**

- ★ Gamma decay is almost instantaneous: the exception is when the initial state is **meta-stable** (i.e. there is low probability of transition to ground state)
- ★ The other way to release energy surplus:  
**INTERNAL CONVERSION**

# Radioactive nuclei die but don't get old

- ✦ Radioactive nuclei do not transform gradually, but suddenly, in random manner
- ✦ Unstable nuclei has certain **probability** of decay in unit of time =>

RADIOACTIVE DECAY LAW



# Radioactive decay law:

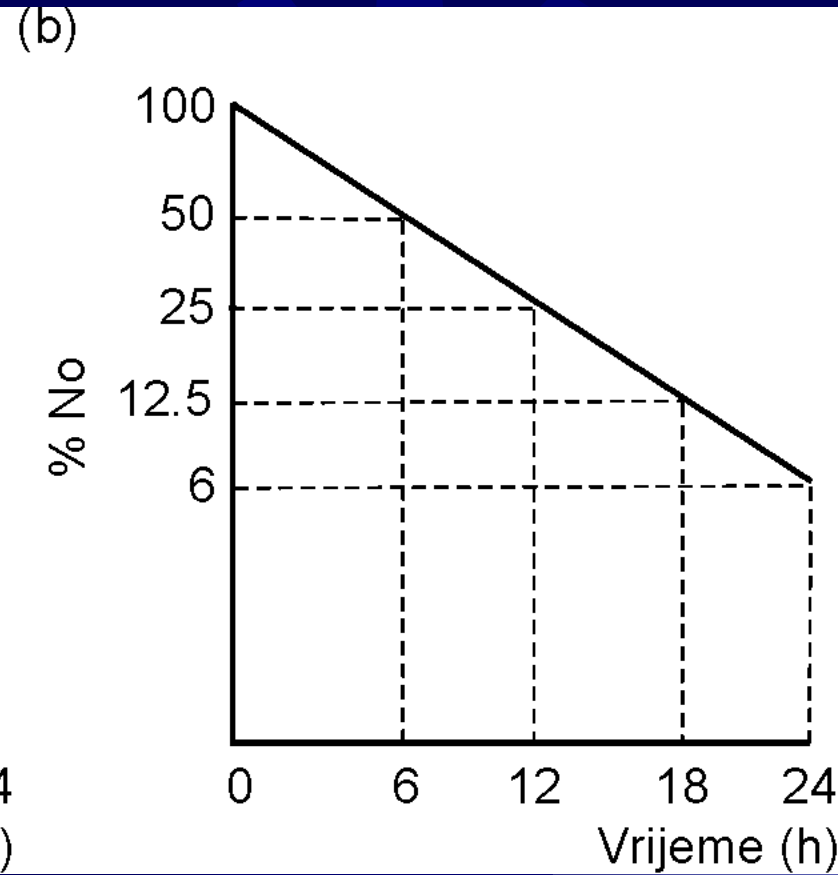
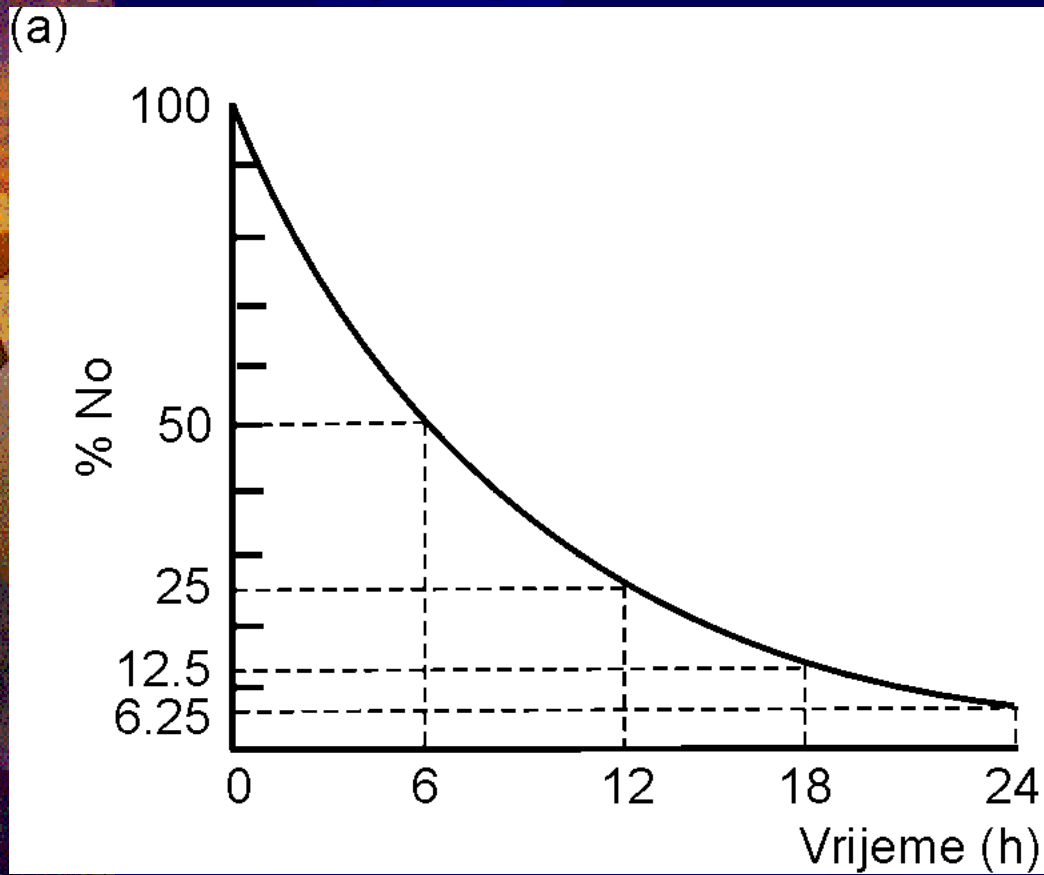
$$N = N_0 \times e^{-\lambda t}$$

- $N_0$  the initial number of unstable nuclei
- $N$  the surviving number of nuclei at time  $t$
- $\lambda$  decay constant: probability of transformation (decay) in unit time

## HALF-TIME

Time required for one half of initial unstable nuclei to experience transformation (another half is still live!)

$$T_{1/2} = 0.693 / \lambda$$



Decay of Tc-99 in linear (left) and logarithmic scale (right)

# Radioactivity (activity)

- ★ No of decays of radionuclide in unit time  $-\Delta N(t)/\Delta t$  is **radioactivity** or short **activity**;  $A(t)$ :

$$A(t) = - \Delta N(t)/\Delta t$$

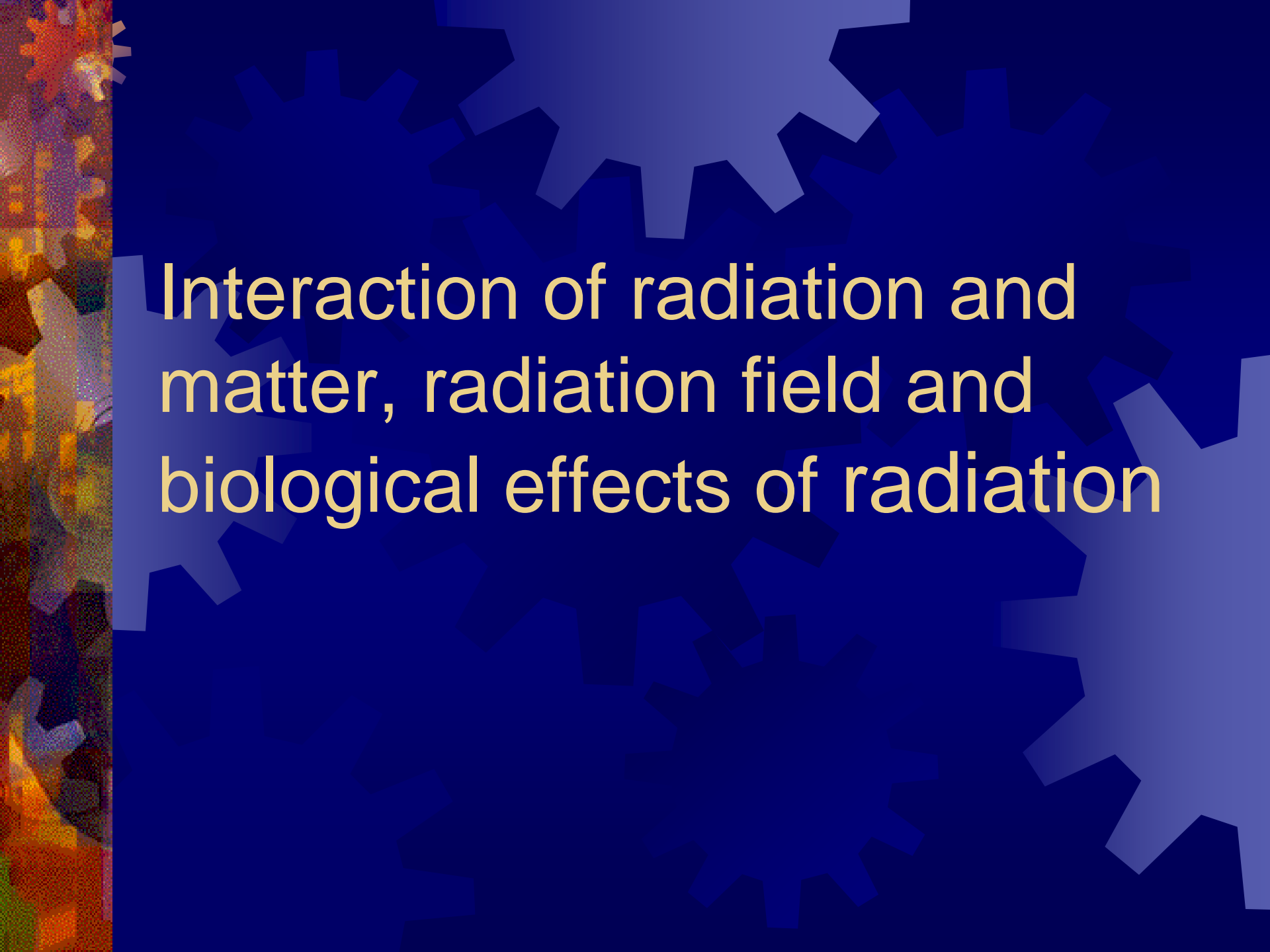
Unit of activity is Becquerel (Bq)

**TABLE 1.1** Half-lives ( $T_{1/2}$ ) of some radionuclides

<b>Radioisotope</b>	<b>Element</b>	<b><math>T_{1/2}</math></b>
<i>Natural</i>		
U-238	Uranium	4.5 billion years
Ra-226	Radium	1600 years
K-40	Potassium	1.3 billion years
C-14	Carbon	5760 years
H-3	Hydrogen	12 years
<i>Artificial</i>		
Cs-137	Cesium	33 years
I-131	Iodine	8 days
I-125	Iodine	60 days
Co-60	Cobalt	5.3 years
P-32	Phosphor	14.3 days
Na-24	Sodium	15 hours
Tc-99m	Technetium	6 hours

**TABLE 1.2** Main characteristics of different modes of radioactive decay

<b>Decay</b>	<b>Parent nucleus</b>	<b>Daughter nucleus</b>	<b>Radiation</b>
alpha	$Z/N$	$Z-2 / N-2$	He-4 nucleus
beta-minus	$Z/N$	$Z+1 / N-1$	electron
beta-plus	$Z/N$	$Z-1 / N+1$	positron
gamma	$Z/N$	$Z/N$	gamma photon



# Interaction of radiation and matter, radiation field and biological effects of radiation

# Contents:

## ▶ Transport of radiation:

Radioactive radiation ionizes matter

Particle radiation gives off energy in small steps

Particle radiation mostly ionizes before stopping

Gamma rays lose energy at once or in couple of steps

Gamma rays penetrate more than particles





## • **Dosimetry:**

Source and field of ionizing radiation

Two quantities describe radiation effects

Radiation effects can be measured or estimated

Absorbed dose can be assessed from exposure

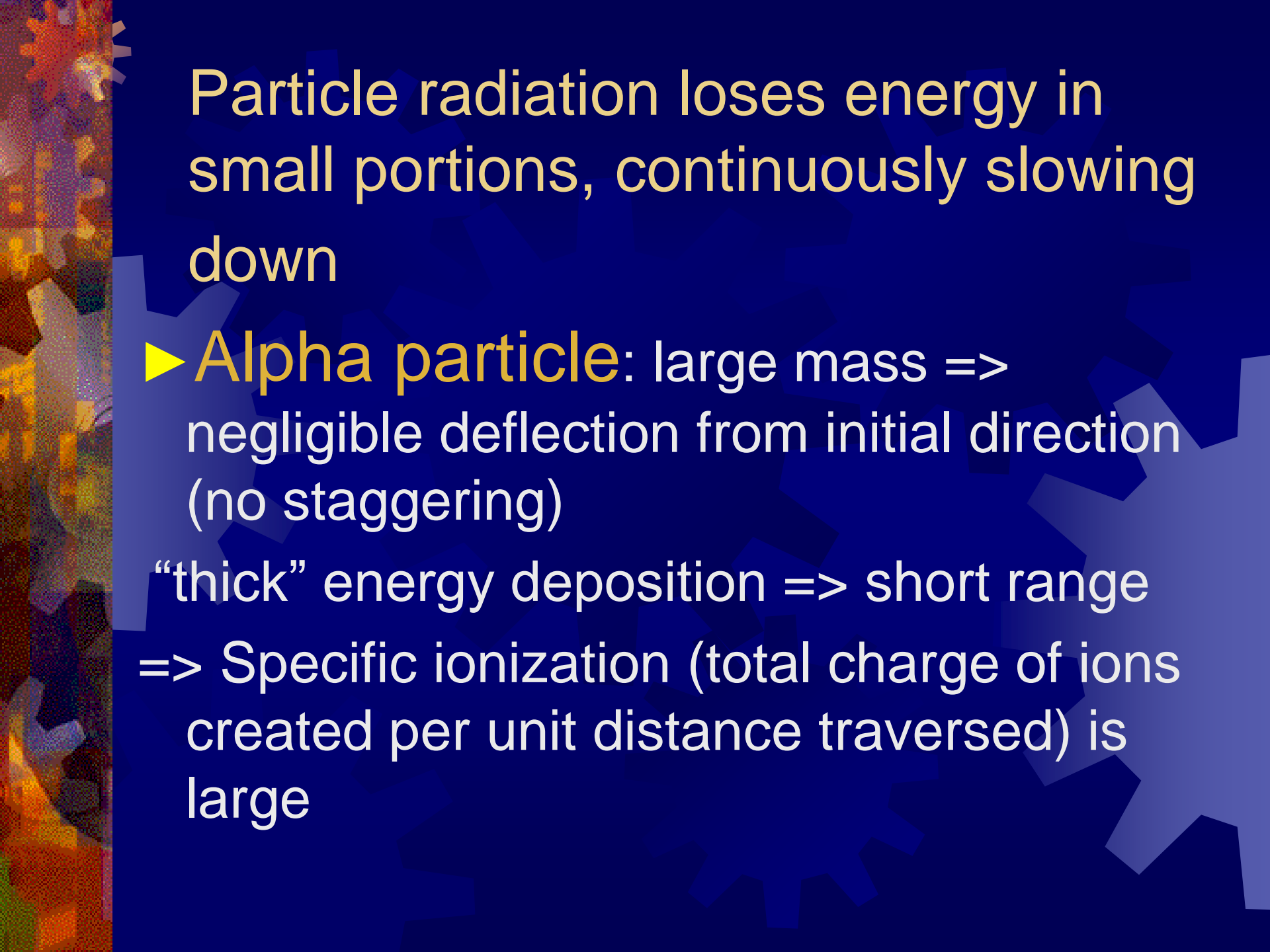
Ionization is biologically harmful

We are most irradiated from natural sources

# RADIOACTIVE RADIATIONS

## IONIZE MATTER

- ▶ Unlike infrared and visible light, high-energy radioactive radiation can eject even tightly bound electrons from atom's inner orbits
- ▶ = **ionization of atom**
- ▶ => **ionizing radiation**



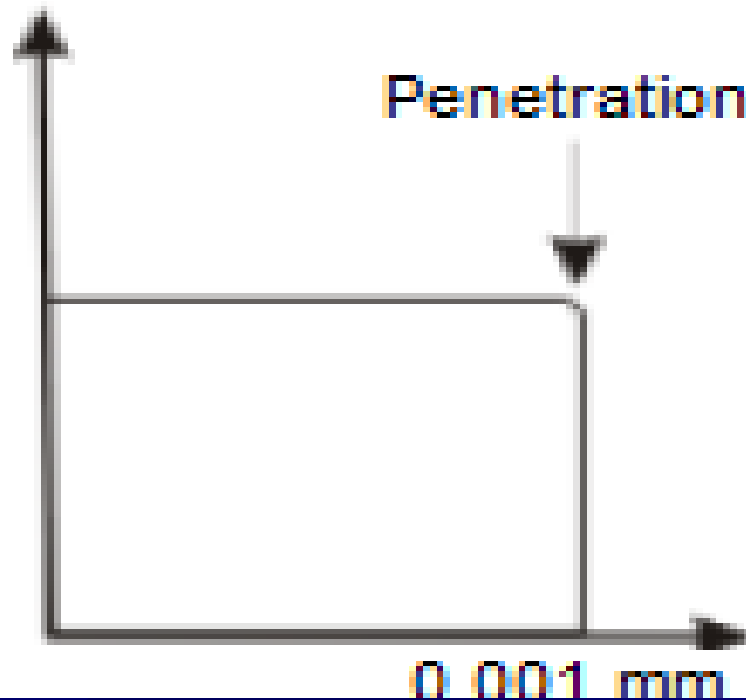
Particle radiation loses energy in small portions, continuously slowing down

▶ **Alpha particle**: large mass => negligible deflection from initial direction (no staggering)

“thick” energy deposition => short range  
=> Specific ionization (total charge of ions created per unit distance traversed) is large

Alpha particles with the same initial energy have the same range in the given material

Number of  $\alpha$  particles  
that reach to the depth  $x$



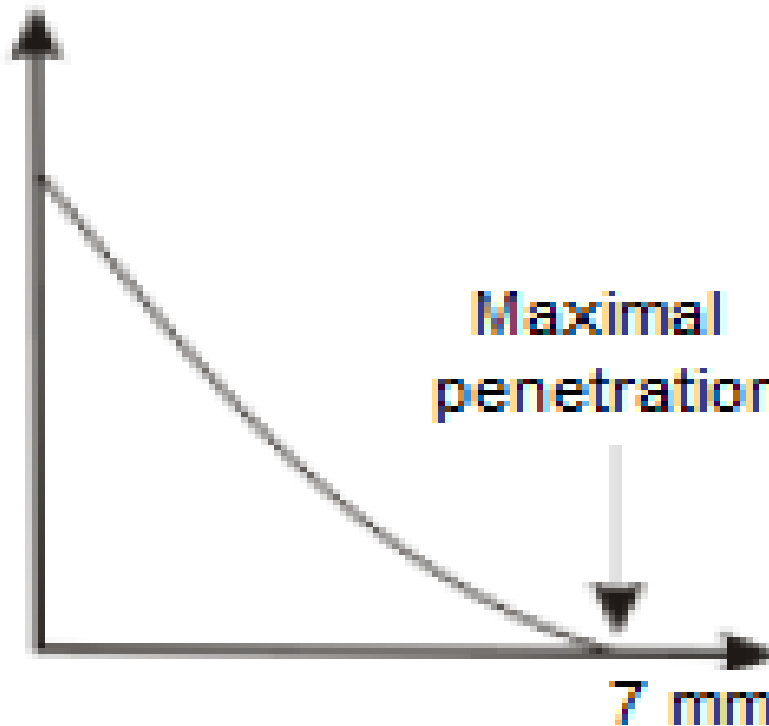


► **Beta particles:** small mass => stagger in colliding with orbital electrons => broken path

Due to curved, broken path the penetration depth is always less than range (total length of path)

Beta particles with the same initial energy do not have the same range

Number of  $\beta$  particles  
that reach to the depth  $x$

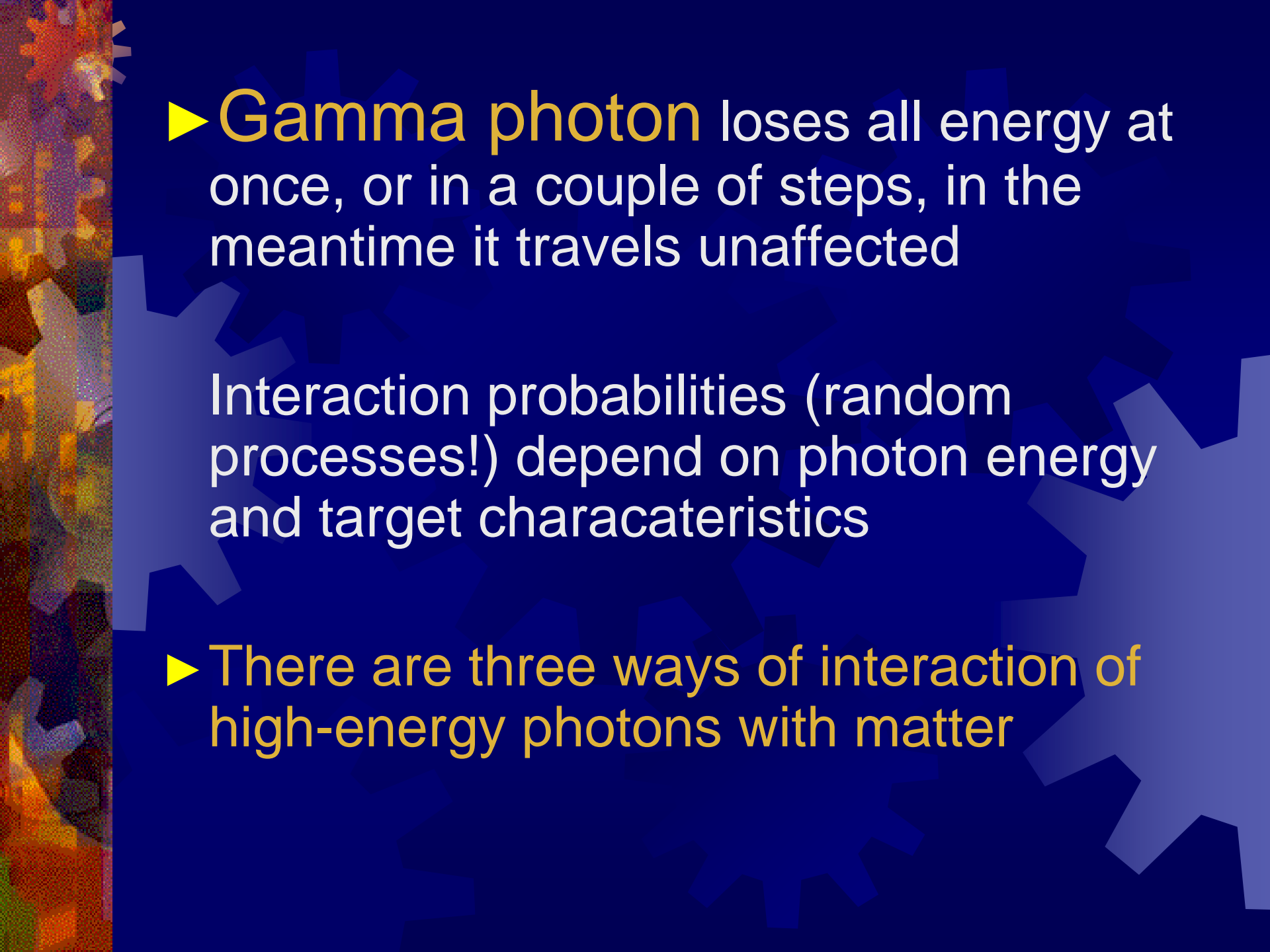




Particle radiation ionizes mostly at the end of journey

▶ ANALOGY:

Slow rock demolishes window glass,  
while rifle bullet makes a hole only

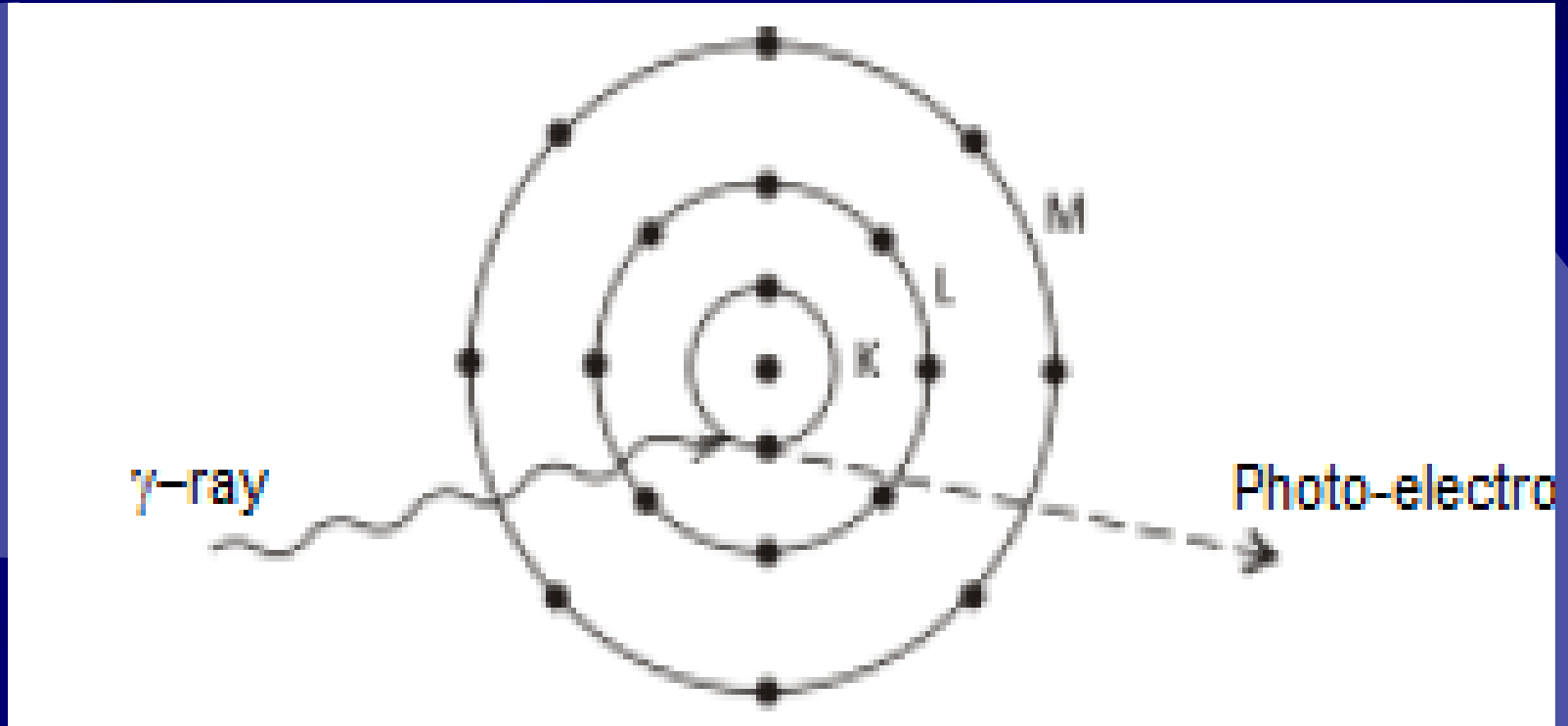
- 
- ▶ **Gamma photon** loses all energy at once, or in a couple of steps, in the meantime it travels unaffected

Interaction probabilities (random processes!) depend on photon energy and target characteristics

- ▶ There are three ways of interaction of high-energy photons with matter



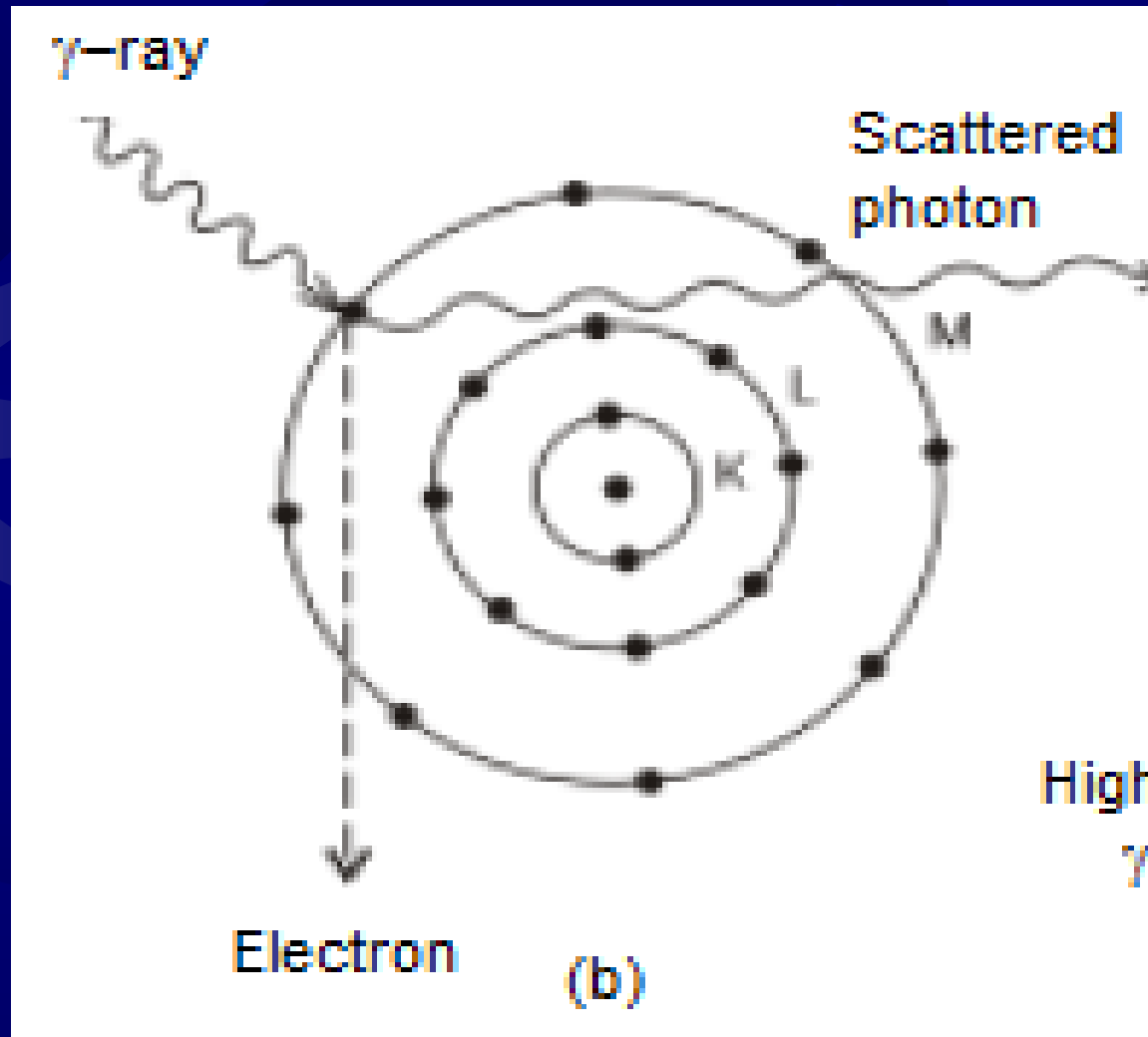
# Photoelectric (photo) effect:



# When photo-effect is likely to happen?

- ▶ In photo-effect high energy photon 'disappears', delivering all of its energy to tightly bound, inner orbital electron, which leaves the atom as the fast, charged particle, performing lots of subsequent ionizations
- ▶ Photo effect is most probable:
  1. In high  $Z$  materials (probability increases with  $Z^3$ )
  2. When photon energy barely exceeds the energy of ionization of K-electron (the rest is kinetic energy of freed electron)

# Compton scattering (effect)



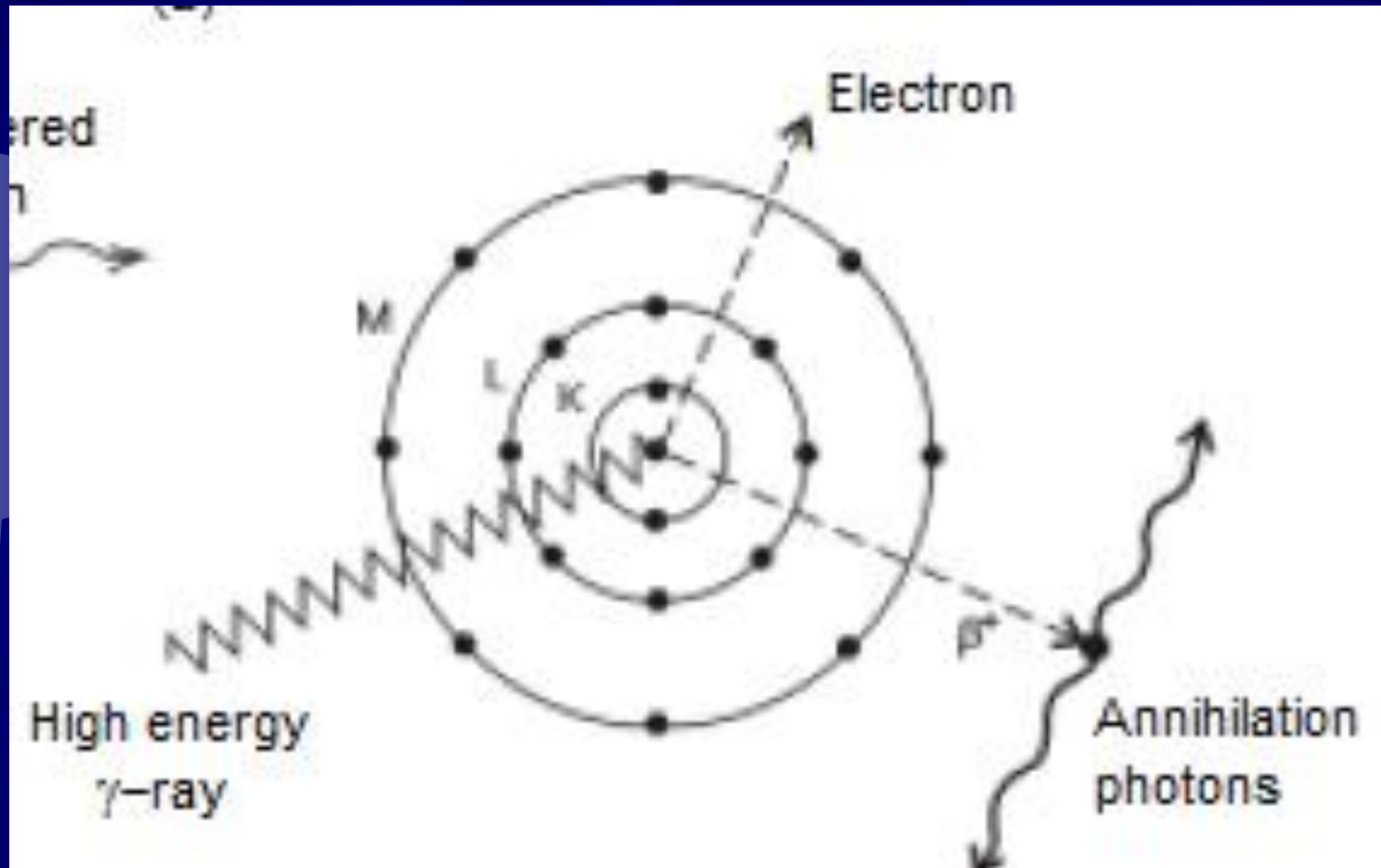
# When Compton-effect is likely to happen ?

▶ In Compton-effect high energy photon loses a part of its energy, which is delivered to free or loosely bound atom electron. The lower energy photon leaves the battlefield in other direction (small deflections are more probable than large ones), while the electron leaves the atom as the fast, charged particle, performing lots of subsequent ionizations

▶ Compton scattering:

1. Does not depend on  $Z$  (elements in absorber), only density of free (loosely bound) electrons matter (which is roughly proportional to absorber density)
2. In analogy with collision of balls of equal masses, is most probable when photon energy equals the energy equivalent of electron mass (511 keV).

# Pair production effect



# When pair production is possible ?

- In pair production, very high energy photon ( $E_\gamma$  above 1.024 MeV), in the vicinity of heavy nucleus, disappears, its energy re-emerges as the electron-positron (anti-electron) pair
- Pair production is always accompanied by annihilation radiation, after slowed positron collides with electron, both disappear, creating two gamma photons of 511 keV energy, going in opposite direction
- Only for photons with high energies interacting with high-atomic-number elements

# Photons vs. particles

- ▶ Gamma (or X photons) ionize indirectly; only first (photo-effect), or eventually a couple of first (Compton scattering), out of thousands of ionizations, are the direct ones. The rest is due to fast electrons, released upon primary ionization.
- ▶ Gamma photons either disappear or go unchaned, thus they have no defined range, but are deflected from initial beam in exponentially decaying manner (analogy with law of radioactive decay!!!)

# Gamma rays penetrate more deeply than particle radiation: difficult protection

- ▶ Intensity of photon beam (power per unit cross-sectional area),  $I_0$  decays exponentially, upon traversing the depth of an absorber  $d$ :

$$I = I_0 e^{-\mu d}$$

- ▶  $\mu$  – linear attenuation coefficient – total probability of all processes that absorb photon or deflect it from initial direction (depends on photon energy and medium characteristics (increases with absorber density and atomic number))

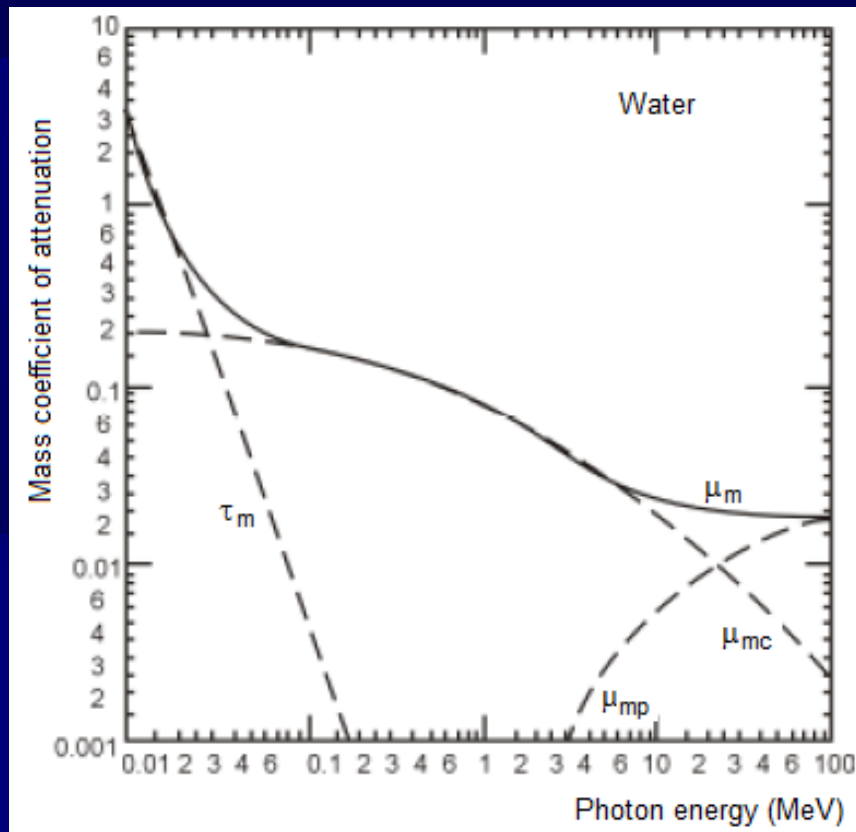


## Half-value thickness

- ▶ Depth of an absorber which makes halve of intensity of photon radiation disappear or deflect from initial direction:

$$d_{1/2} = \ln 2 / \mu$$

It is inversely proportional to linear attenuation coefficient



Mass attenuation coefficient  $\mu_m = \mu/\rho$ , ( $\rho$  is absorber density), shown as the sum of three components: mass coefficient for photo-effect ( $\tau_m$ ), Compton effect ( $\mu_{mc}$ ) and pair creation ( $\mu_{mp}$ ). Note that probability of photo-effect decreases with increasing photon energy, when Compton effect prevails.

# Source and field of radiation

- ▶ Source characteristics:
  1. Geometry
  2. Type of radiation, energies, decay rate
  3. Current number of unstable nuclei ( $N_0$ )

Current source activity:  $A_0 = \lambda N_0$

# Source power and intensity of radiation

- ▶ Power is given from source activity, type and energy of radiations
- ▶ From source power (P) one calculates **intensity of radiation**  $I = P/\text{unit area}$  around point of interest in the **radiation field** (the space where radiation is present)

# Radiation intensity decays with square distance from the source

- ▶ Due to uniform emission of radiation in all directions from the source, in vacuum (no interaction prior to point of interest), radiation energy dissipates over increasingly larger spherical shells:

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

=> BASIC PROTECTION RULES

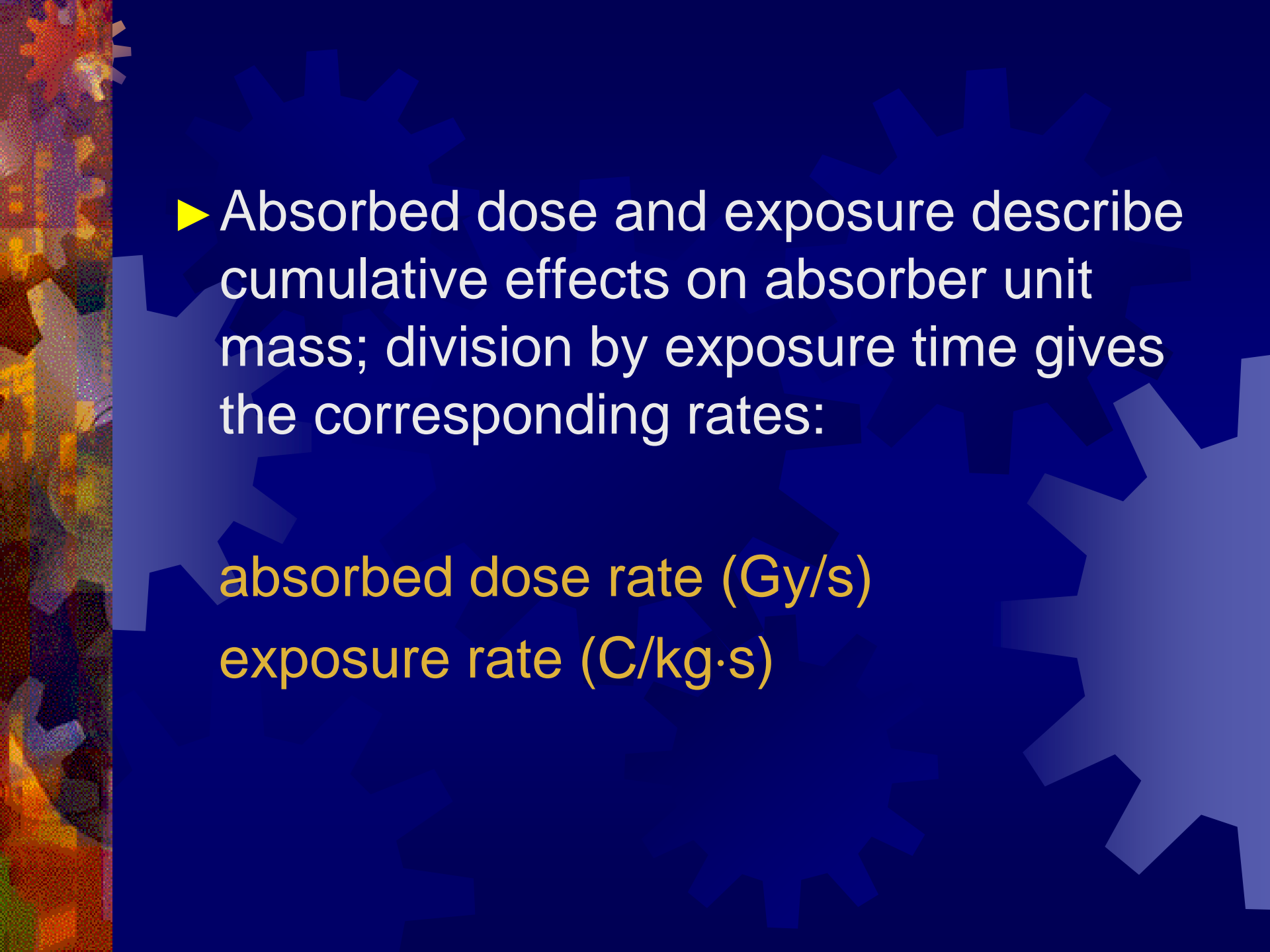
1. shortest possible exposure
2. maximal distance from the source (more efficient than 1.)
3. use of absorber shields

## 2 quantities describe radiation effects

- ▶ **Absorbed dose** (energy delivered to unit mass of medium), unit: Grey (Gy)  
 $1 \text{ Gy} = 1 \text{ J/kg}$
- ▶ **Exposure** (total charge released by radiation in unit mass of air, unit: C/kg: defined only for electromagnetic (non-particle) radiation)

# Typical radiation doses

Source	Absorbed dose (mGy)
Natural radiation	1-5 a year
Single chest X-rays	
Best (smallest)	0.1
Average	2
Fluoroscopic examination	100
Local radiotherapy	30 000-70 000

- 
- ▶ Absorbed dose and exposure describe cumulative effects on absorber unit mass; division by exposure time gives the corresponding rates:

absorbed dose rate (Gy/s)

exposure rate (C/kg·s)



# Radiation effects can be measured or assessed

- ▶ In case of point source the exposure rate is constant on surface of a sphere having radius  $R$ , and is proportional to source activity,  $A$ :

$$\text{Exposure rate} = \Gamma A/R^2$$

$\Gamma$  - proportionality constant; depends on gamma photon energy, describes different effects of gamma sources of the same activity. Larger energy gamma sources have larger gamma constants.

# Radiation parameters of several radionuclides

**TABLE 1.6.** Radiation parameters of common radionuclides

	$E_{\gamma}$ (keV)	$\Gamma(\text{Cm}^2/\text{kg Bq s}) \times 10^{14}$	$\mu$ ( $\text{cm}^{-1}$ ) –in lead
Tc-99m	140	0.14	23
Hg-203	279	0.23	2.3
I-131	360	0.43	2.3
Au-198	412	0.45	2.3
F-18	512	1.11	0.76
Cs-137	667	0.60	1.20
Co-60	1250	0.52	0.58

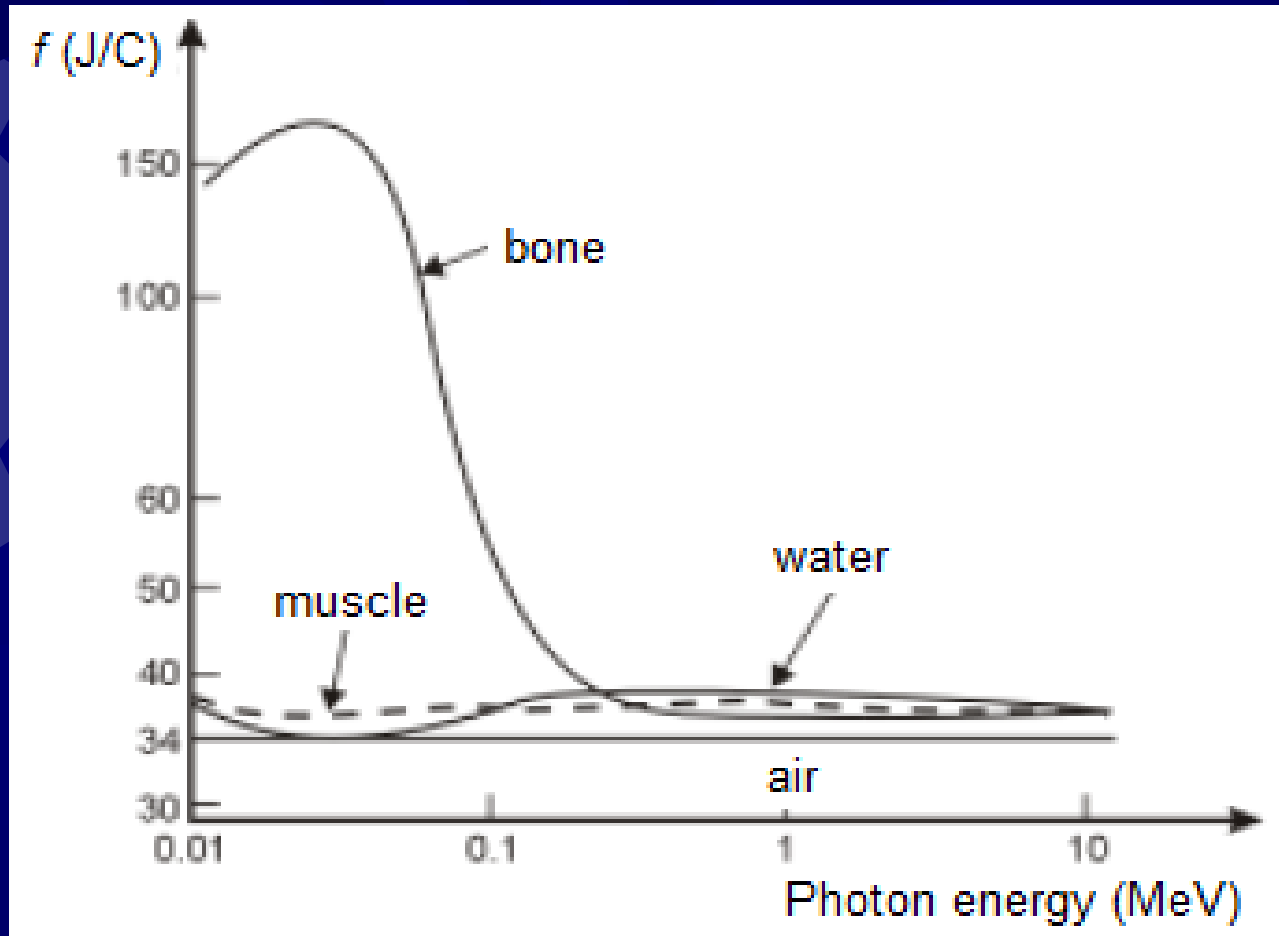
# Absorbed dose can be assessed from measured exposure

- ▶ If absorber is living tissue, the absorbed dose reflects the biological damage induced by radiation. In case of gamma and X photons:

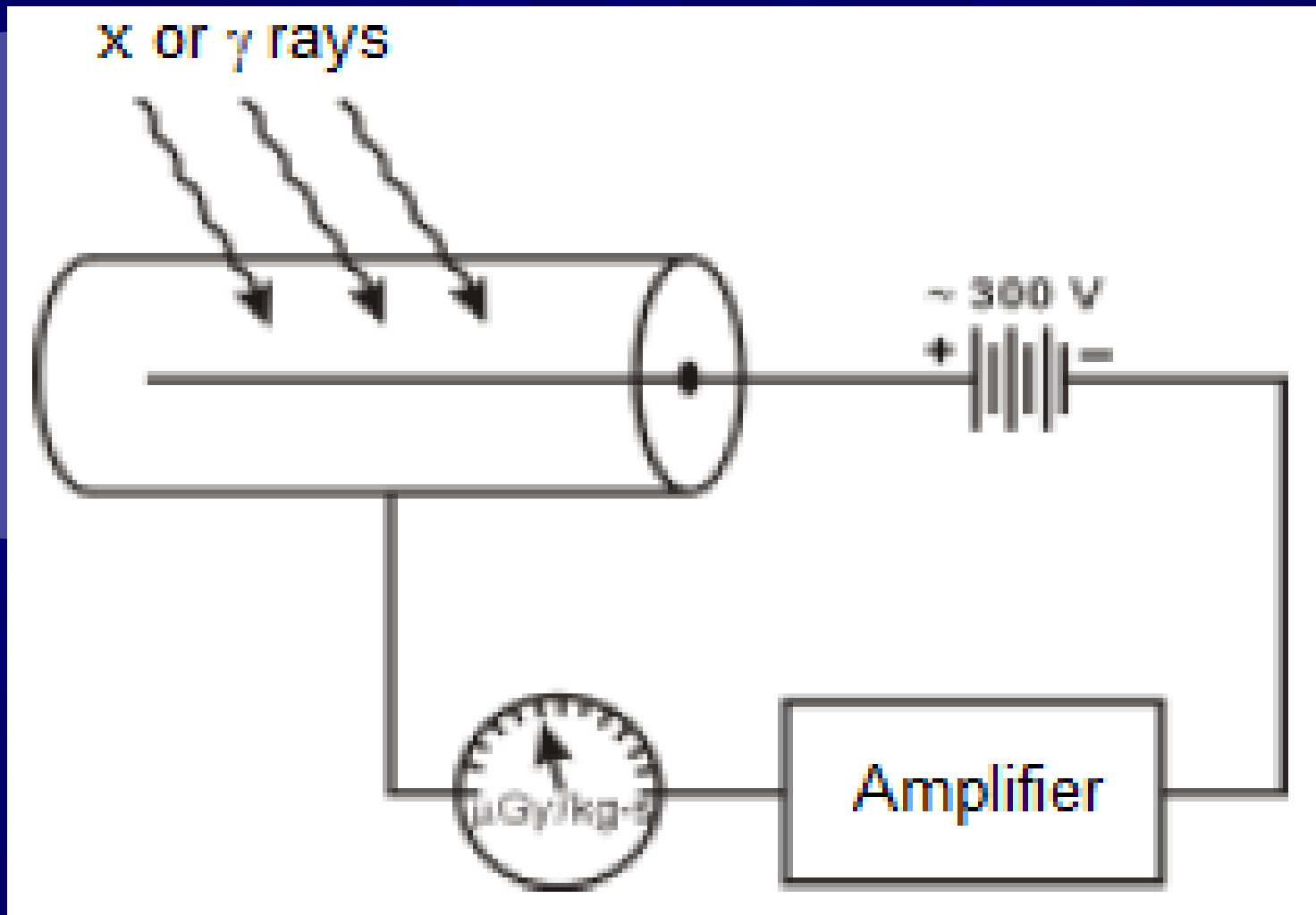
$$\text{absorbed dose (Gy)} = f \cdot \text{exposure (C/kg)}$$

where  $f$  depends both on absorber and photon energy

Ratio of absorbed dose and exposure (f) depends on photon energy variously in different tissues



# Exposure is measured by **ionization chambers**



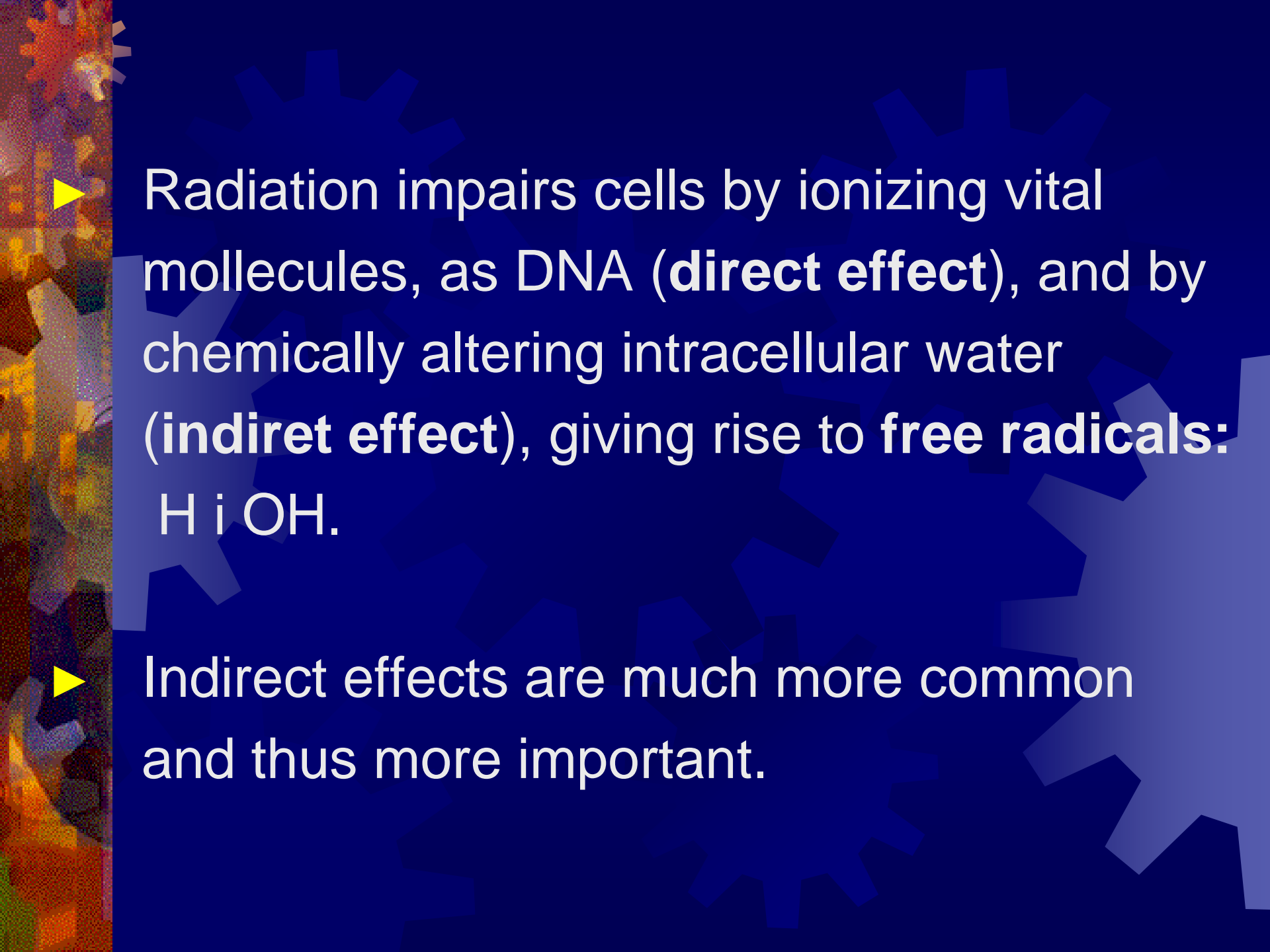
# Geiger-Müllerov (GM) counter

- ▶ Voltage is higher and primary ions, on their way towards the electrodes, produce an avalanche of secondary ions. This internal amplification has:
- ▶ **Advantage:** relatively low energy ionizing radiation can be detected
- ▶ **Disadvantage:** GM counters lose information on primary ionizations, and thus cannot measure exposure, only number of ionizing events in a given time

# Ionization is biologically harmful

Cells can be seriously impaired, depending on:

- ▶ (i) tissue exposed (proliferative cells are most sensitive)
- ▶ (ii) absorbed dose
- ▶ (iii) type of radiation
- ▶ (iv) dose rate (longer time enables recuperation)



▶ Radiation impairs cells by ionizing vital molecules, as DNA (**direct effect**), and by chemically altering intracellular water (**indirect effect**), giving rise to **free radicals**:  
 $H \cdot$  and  $OH \cdot$ .

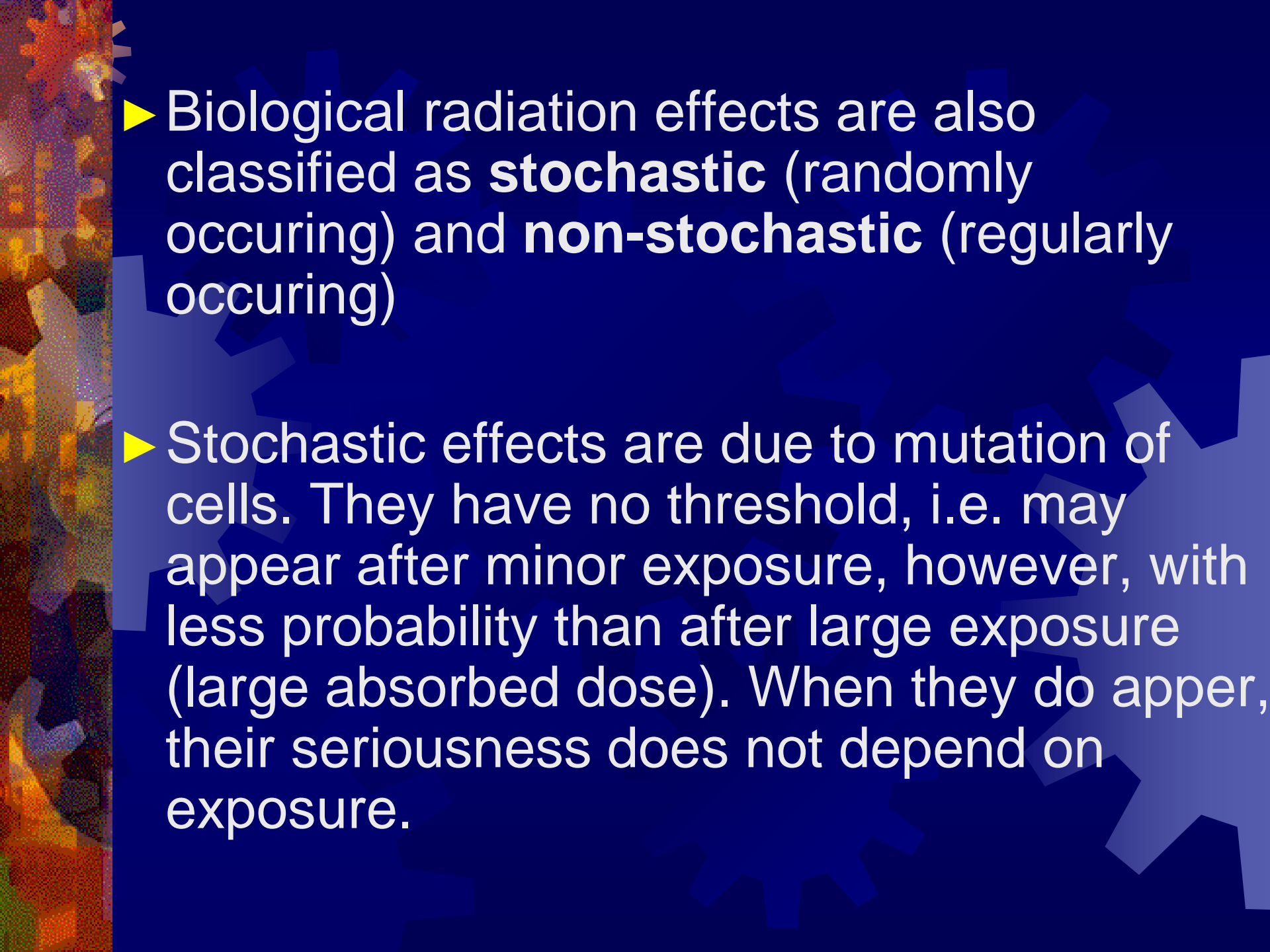
▶ Indirect effects are much more common and thus more important.



The background is a dark blue field filled with various sizes of semi-transparent gears. On the left side, there is a vertical strip with a colorful, textured pattern in shades of orange, red, and brown, resembling a microscopic view or a complex material.

# Radiation effects can be hereditary or somatic

- ▶ **Hereditary effects** are due to impairment of reproductive cells, do not affect the person exposed, but her (his) offspring
- ▶ **Somatic effects** affect only the person exposed to radiation

- 
- The background features a dark blue field with several large, semi-transparent gears of various shades of blue. On the left side, there is a vertical strip with a complex, colorful pattern of orange, yellow, and brown, resembling a textured surface or a microscopic view. The text is presented in a clean, white, sans-serif font.
- ▶ Biological radiation effects are also classified as **stochastic** (randomly occurring) and **non-stochastic** (regularly occurring)
  - ▶ Stochastic effects are due to mutation of cells. They have no threshold, i.e. may appear after minor exposure, however, with less probability than after large exposure (large absorbed dose). When they do appear, their seriousness does not depend on exposure.

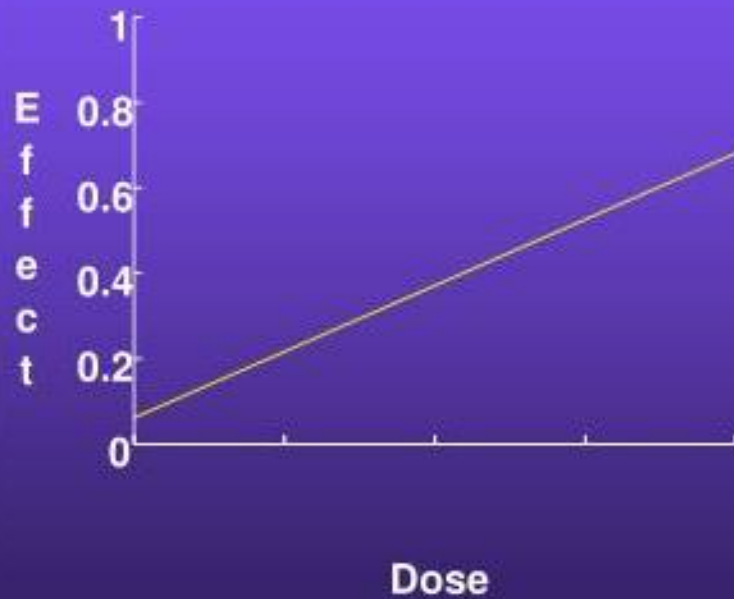
## **Radiation Effects**

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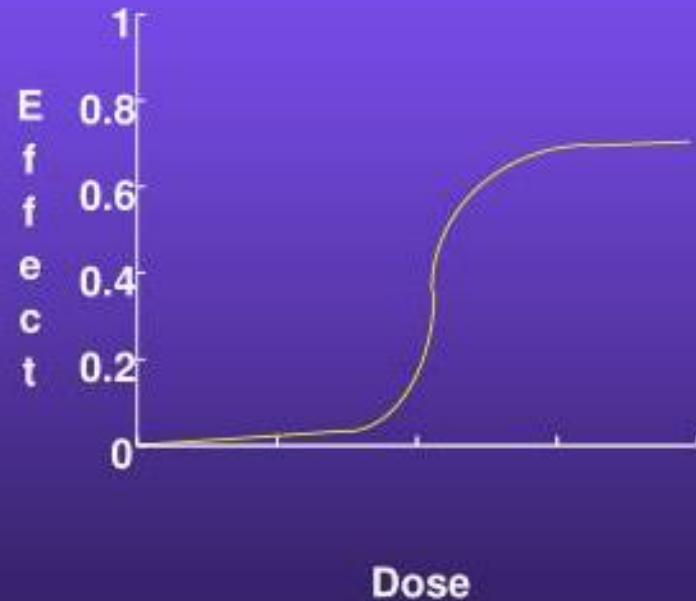
- **Stochastic** - “All-or-Nothing” Effect  
Occurrence Probability is Function of Dose
  - Increased Risk of Developing Cancer
  - Inheritable Mutations
- **Deterministic** -  
Effect Severity is a Function of Dose  
(Commonly Associated with Threshold)
  - Inflammatory Response
  - Organ Failure
  - Fibrosis

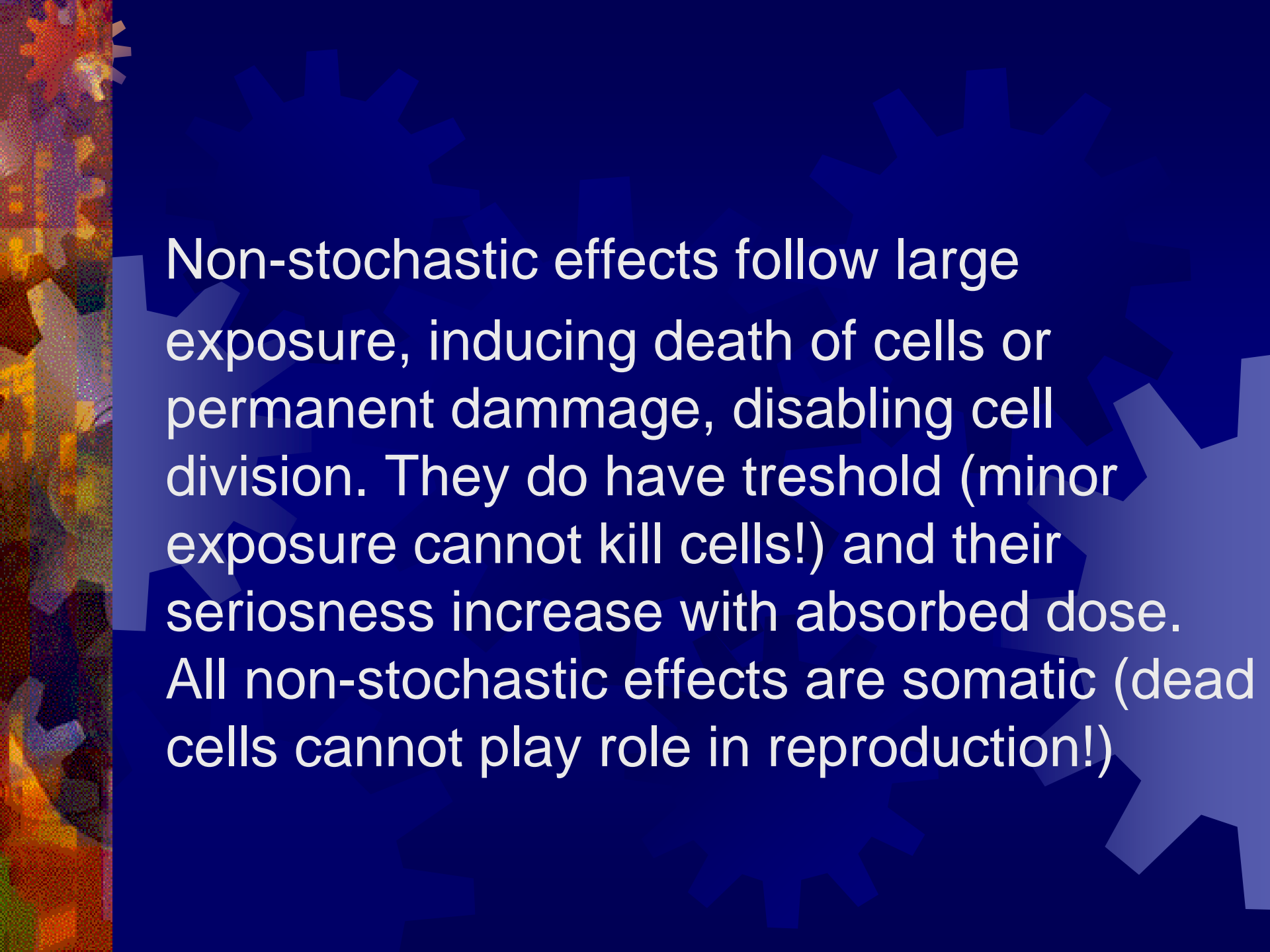
# Radiation Effects

Stochastic

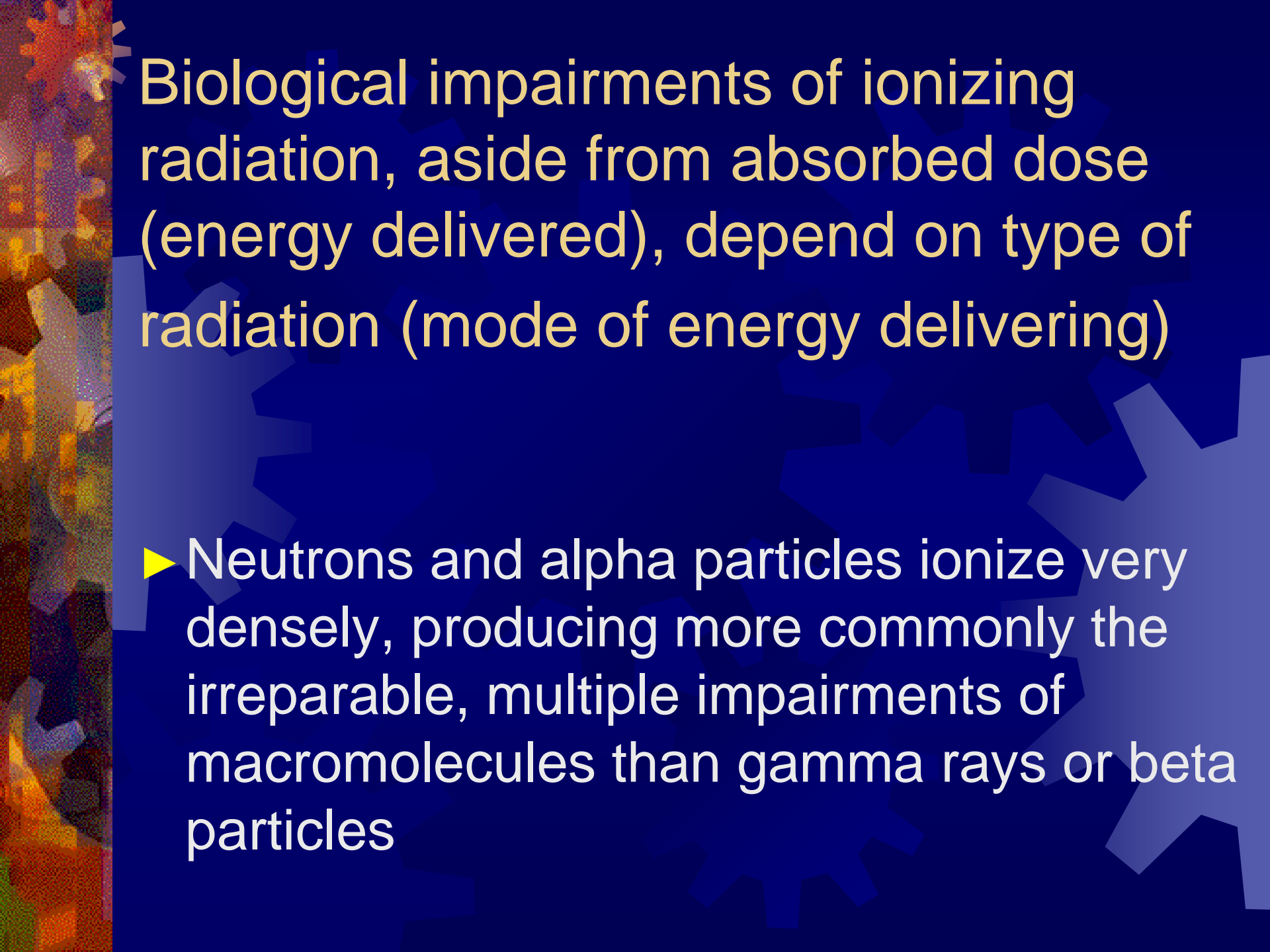


Deterministic





Non-stochastic effects follow large exposure, inducing death of cells or permanent damage, disabling cell division. They do have threshold (minor exposure cannot kill cells!) and their seriousness increase with absorbed dose. All non-stochastic effects are somatic (dead cells cannot play role in reproduction!)



Biological impairments of ionizing radiation, aside from absorbed dose (energy delivered), depend on type of radiation (mode of energy delivering)

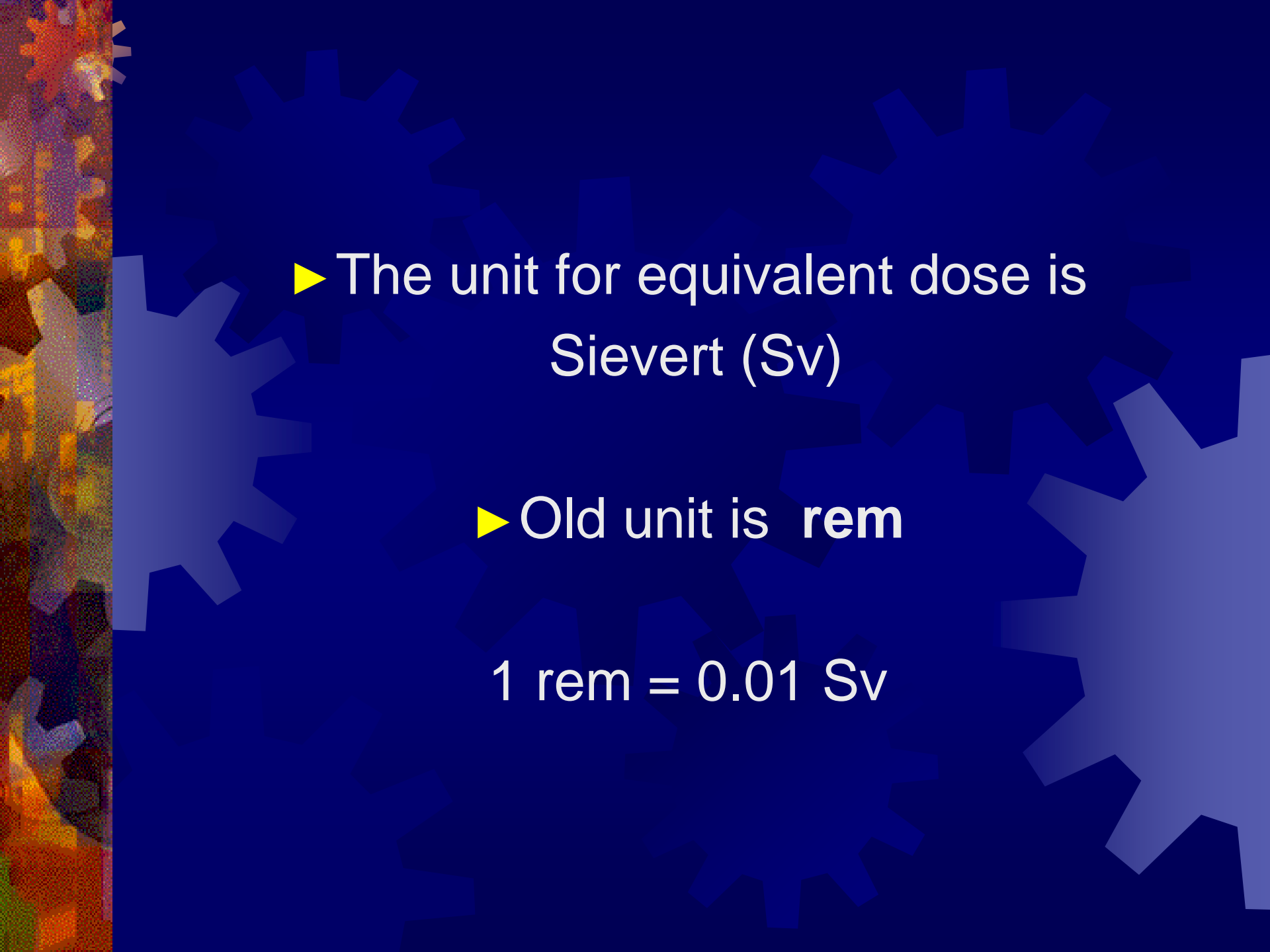
- ▶ Neutrons and alpha particles ionize very densely, producing more commonly the irreparable, multiple impairments of macromolecules than gamma rays or beta particles

# Equivalent dose

$$\text{Equivalent dose} = Q \cdot \text{Absorbed dose}$$

$Q$  is **quality factor**. For alpha particles, it equals 20, for neutrons from 5 to 20 (depending on energy), and for beta particles, X and gamma photons- 1





▶ The unit for equivalent dose is Sievert (Sv)

▶ Old unit is rem

$$1 \text{ rem} = 0.01 \text{ Sv}$$



# Effective equivalent dose

- ▶ Sensitivity to radiation exposure (radiosensitivity) is different in different tissues; to account for it, to every body part one assigns the weight factor according to specific radiosensitivity:
- ▶ **effective equivalent dose (Sv) =**  
= specific factor x equivalent dose



# We are most irradiated by natural radioactivity sources

- ▶ We are all constantly in the low intensity field of ionizing radiation from various sources (including our own tissues!).

This is **background radiation**

- ▶ Mostly, the radiation sources are natural



## Minor degree of irradiation is due to artificial sources

- ▶ 95% of irradiation from artificial sources is due to medical diagnostics (radiotherapeutic exposure is not taken into account)

# Average effective equivalent dose of Great Britain inhabitants (1991)

Source	Dose/ $\mu$ Sv	Percent	Notion
<u>Natural sources</u>			
Radon	1300	50.1	
Gamma rays from soil and construction materials	350	13.5	
Natural radionuclides in food	300	11.6	
Cosmic radiation	260	10.0	airplane crews can get 10 times more
<u>Artificial sources</u>			
Medical use	370	14.3	excluding radiotherapy
Professional exposure	7	0.27	
Radioactive falls	5	0.19	declining from 1962, except for
Chernobyl accident in 1986			
Leakage of radionuclides	0.4	0.02	
Common market devices	0.4	0.02	smoke detectors, illuminating
watch-heads, etc.			

The end