Department of Medical and Biological Physics

Thermal and Ionizing radiation

Lecture 7

Overview

- Thermal radiation. Absolute black-body. Laws of the black-body radiation.
- X-rays. Nature, sources, use in medicine
- Ionizing radiation. Types, detectors, doses, and biological effects of ionizing radiation

- Thermal (heat) radiation is electromagnetic radiation (equilibrium radiation) emitted by any object with temperature higher than absolute null and related to the thermal motion of its atoms and molecules.

Characteristics of Heat Radiation

Radiant exitance **R_e**	**Radiated energy (E) per unit of surface (A) and unit of time (t) [W/m²]**	$R_e = \frac{E}{A \quad t}$
Spectral density of radiant exitance **r_λ**	Radiant exitance for narrow wavelength interval $\Delta\lambda$ per this wavelength interval	$r_\lambda = \frac{\Delta R_{e\lambda}}{\Delta\lambda}$
Spectral absorption coefficient **α_λ**	Ratio of absorbed energy to all incident energy for narrow wavelength interval $\Delta\lambda$	$\alpha_\lambda = \frac{E_{abs\,\lambda}}{E_{i\,\lambda}}$

Absolute Blackbody

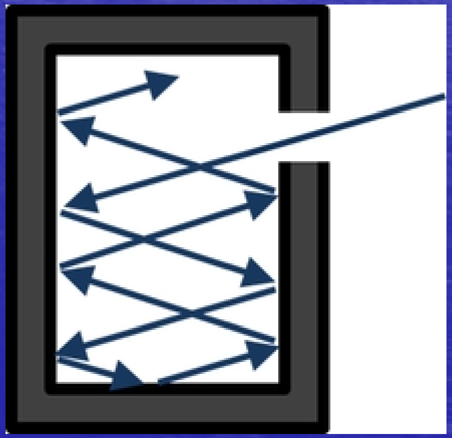
If a body absorbs all incident energy, regardless of frequency ($\alpha_\lambda = 1$)

it is called

an absolute blackbody.

Examples: a eyepupil,

a black velvet, soot

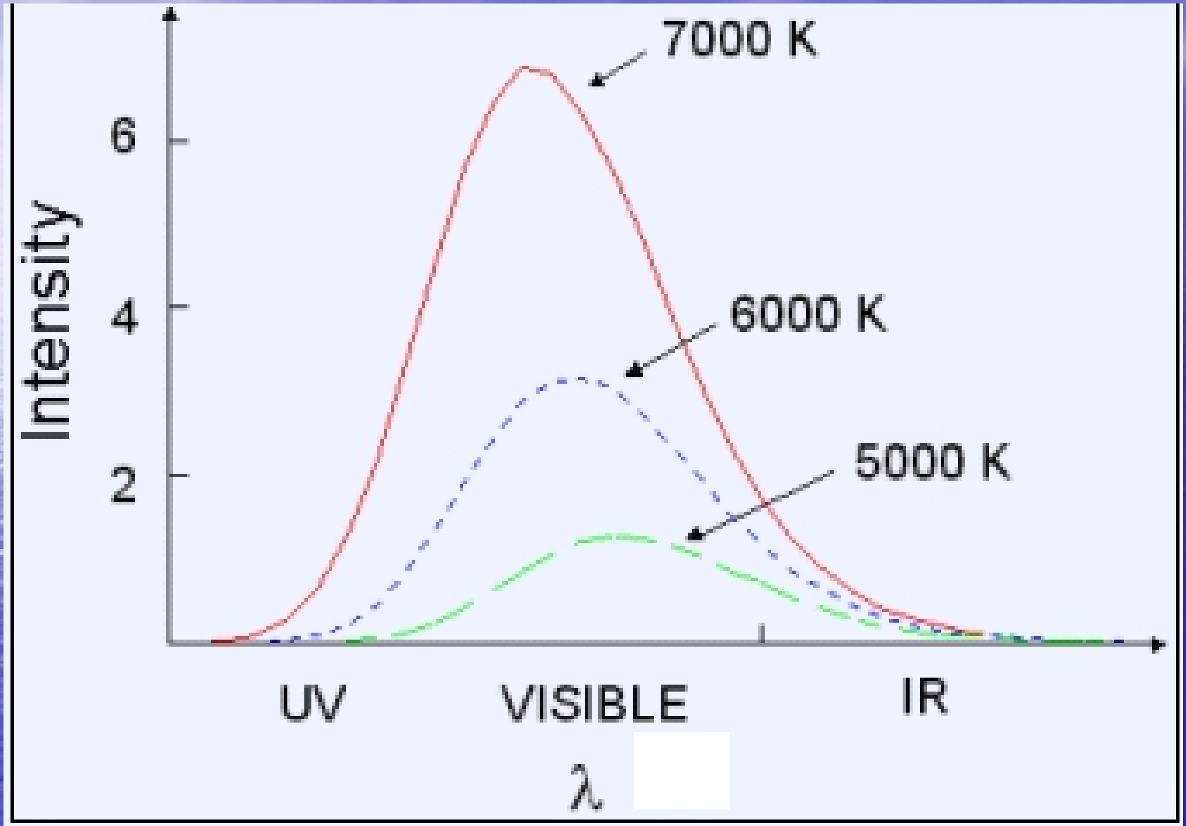


A widely used model of a black surface is a small hole in a cavity with walls that are opaque to radiation.

Laws of Blackbody Radiation

Name	Formula	Description
Kirchhoff's law	$(r_{1\lambda}/\alpha_{1\lambda})_T = (r_{2\lambda}/\alpha_{2\lambda})_T = \ldots = (\varepsilon_\lambda)_T$	Ratio r_λ/α_λ for any body is constant and it is equal to spectral density of radiant exitance of absolute blackbody (ε_λ) at the same T
Stephen-Boltz-mann's law	$R_\lambda = \sigma T^4$ $\sigma = 5.67\times10^{-8}\ W\times m^{-2}\times deg^{-4}$	The radiated energy increases very rapidly with increasing in temperature
Wien's displace-ment law	$\lambda_{max} = b/T$ $b = 0.28978\times10^{-2}\ m\times deg$	The peak of the emission spectrum of the blackbody moves to shorter wavelengths as the temperature increases

Laws of Blackbody Radiation



The peak shifts to short-wave spectral range as temperature increases.

The area under the curve is equal to R_{λ}.

Planck's law

- Electromagnetic energy is radiated and absorbed by portion or quantum $E=h\times f$
- Planck's expression for a spectral density of radiant exitance:

$$\varepsilon_\lambda = \frac{2\pi h c^2}{\lambda^5} \frac{1}{e^{hc/k\lambda T} - 1}$$

- **Thermography** is a diagnostic imaging procedure involving the detection and recording of body thermal flux patterns.

Abnormal tissue in right breast

For a recording of thermogram a photoelectric sensor is used. Operation principle of a photoelectric sensor is based on **the photoeffect phenomenon**

<u>Photoeffect</u> is an electron emission from atoms and molecules of sample (usually metals) under action of electromagnetic radiation.

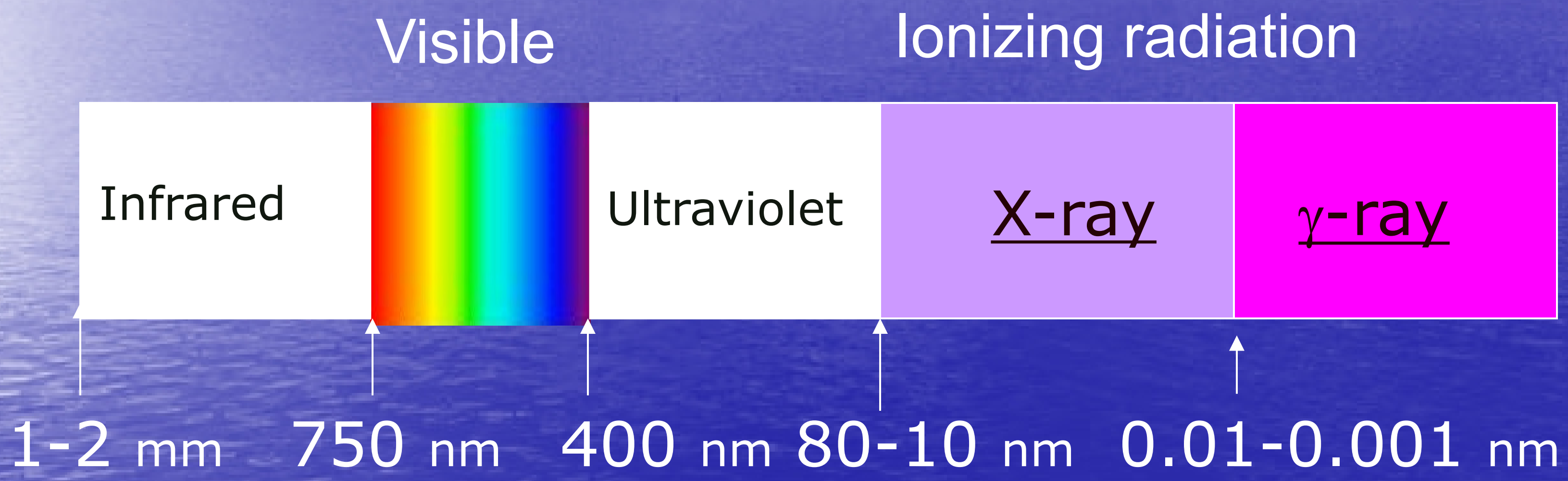
<u>Einstein's formula for the external photoeffect</u>:

$$hf = A + mv^2/2$$

Absorbed energy (E=hf) by the sample is distributed between a work of electron's output from the sample (A) and kinetic energy for electron's motion ($mv^2/2$).

The nature of X-rays and γ-rays

Electromagnetic Spectrum



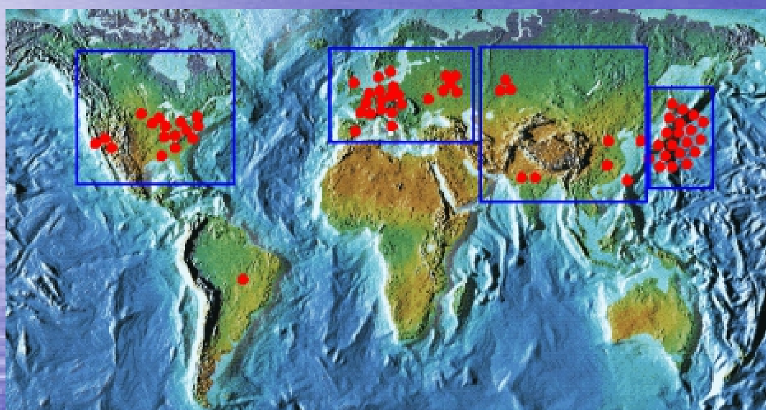
$$E=hf=hc/\lambda$$

X-ray Production Possibilities (sources)

- Electron tubes (medical X-ray electron tube, CRT(cathode ray tube in TV, computer monitor)
- Blackbody Radiation (the sun as an example)
- Radioactive Decay
- Charged-particle accelerators (synchrotron)

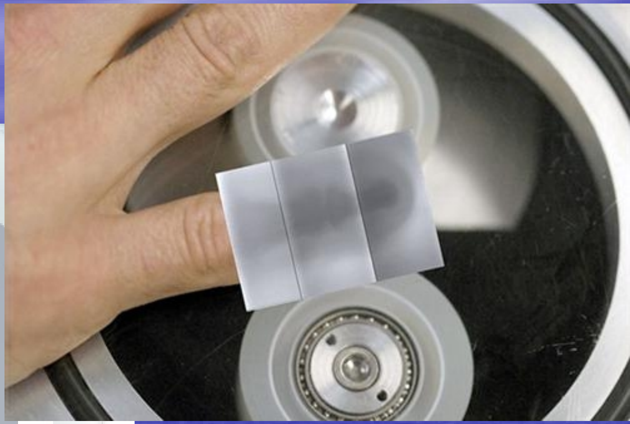
X-ray Production Possibilities (sources)

Charged-particle accelerators (synchrotron)



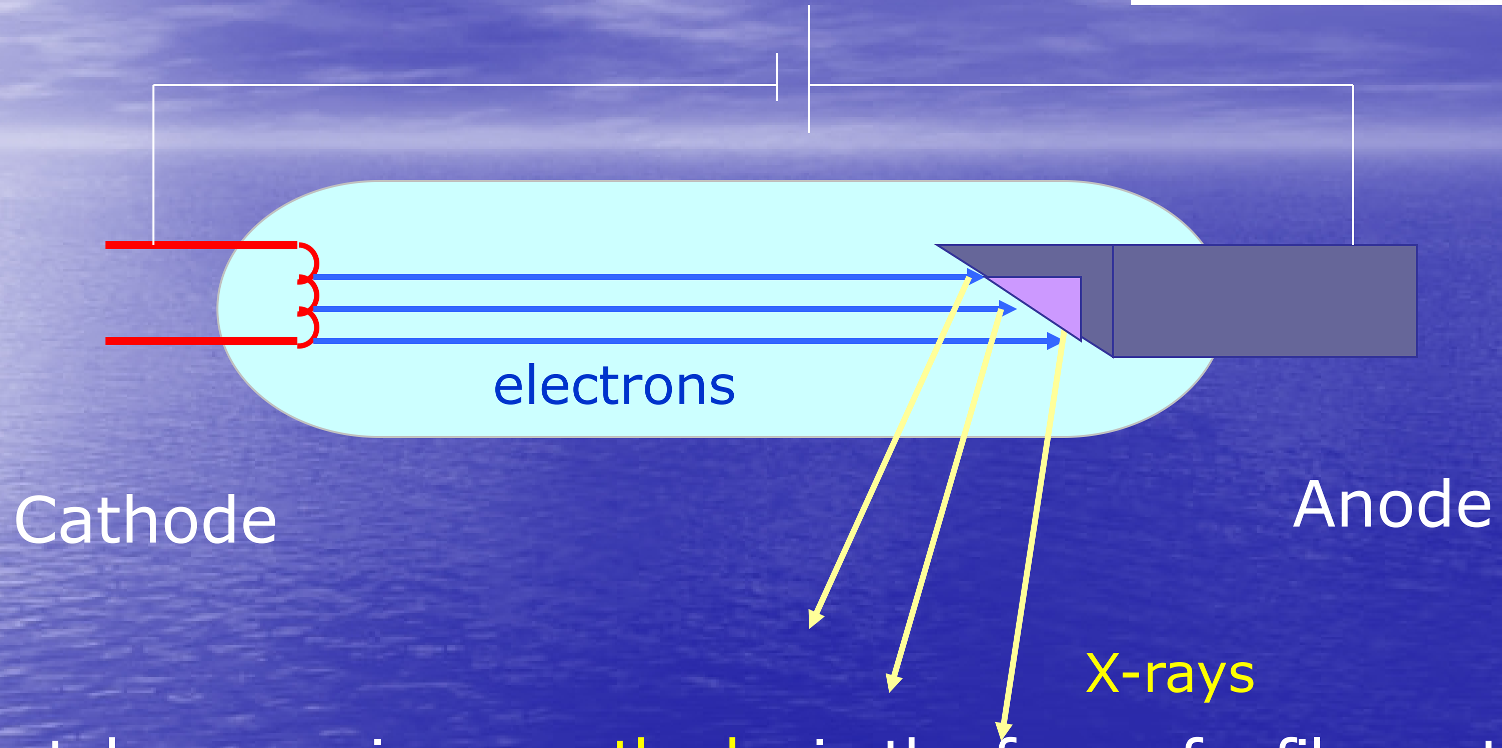
- Synchrotron radiation is emitted by charged particles traveling on a curved path (as would happen while moving through a magnetic field)

X-ray Production Possibilities (sources)



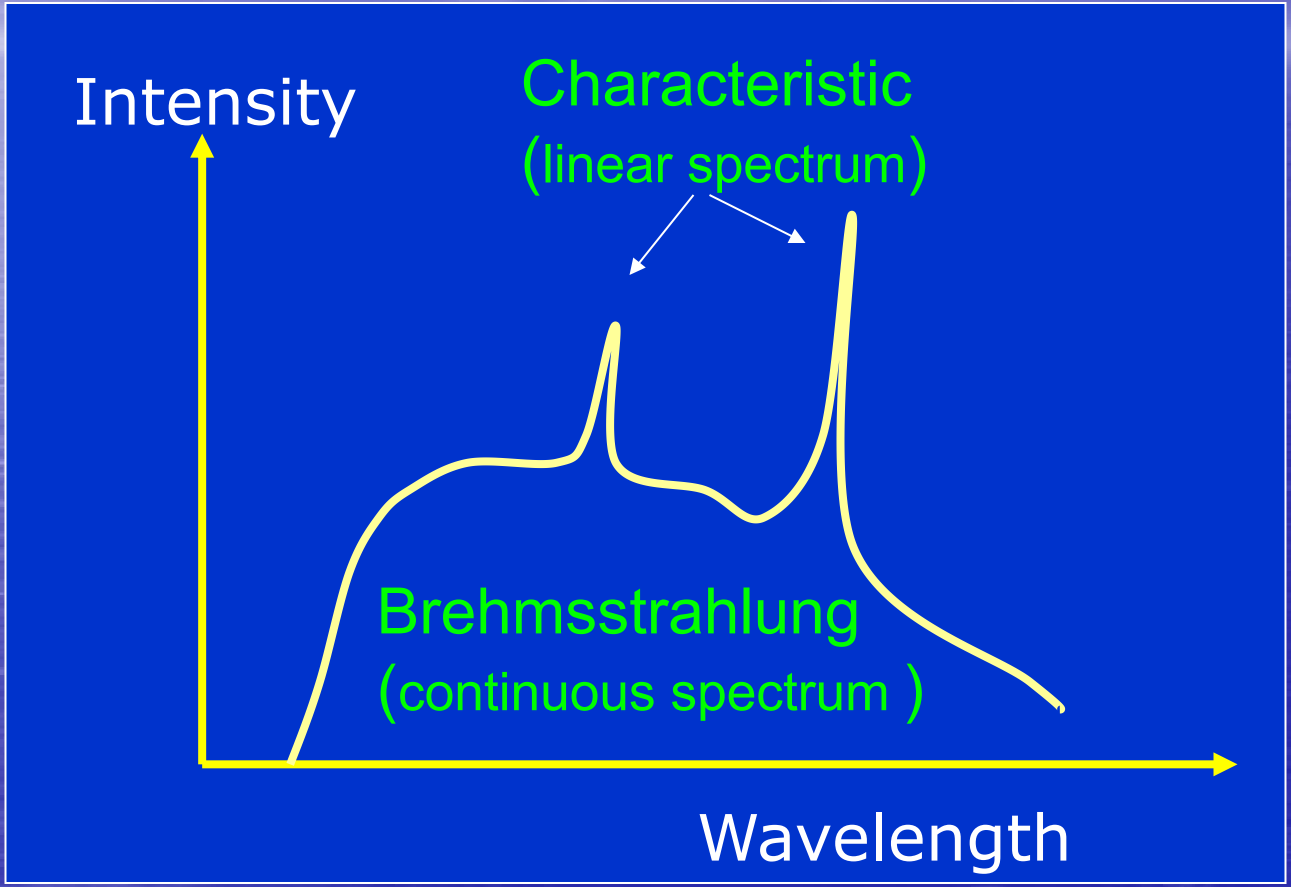
- http://www.nature.com/nature/videoarchive/x-rays/

Electron tube

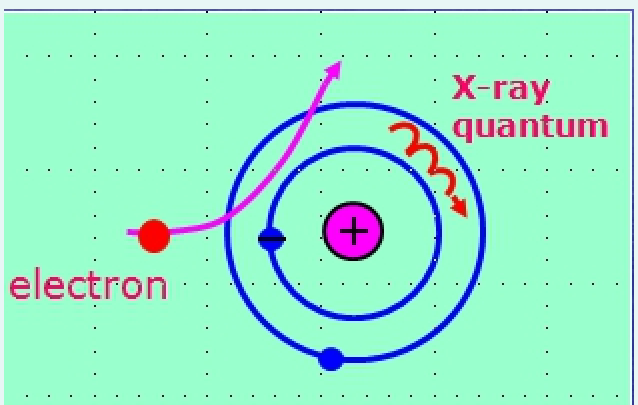


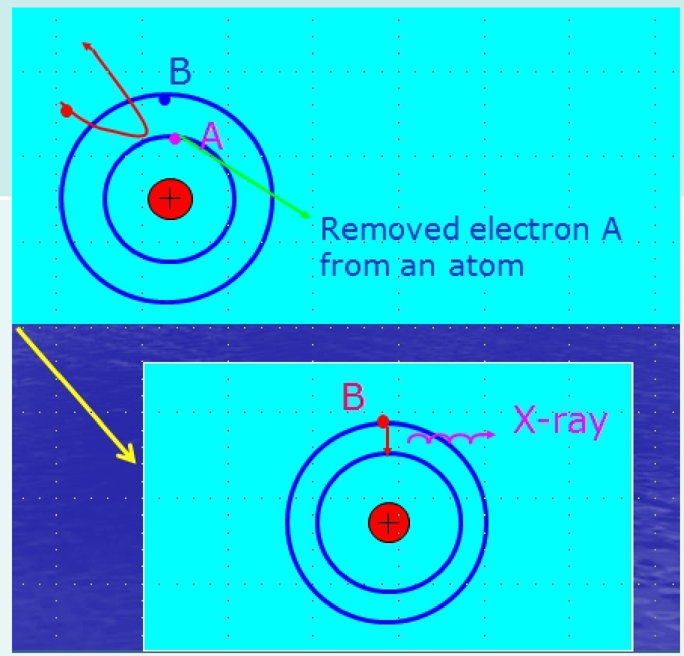
- X-ray tube comprises a cathode, in the form of a filament, and an anode, both in an evacuated container. X-rays are produced when the electrons hit the atom of anode target (copper, molybdenum or tungsten). The electrons slow down and lose kinetic energy in form of x-ray quanta

The X-ray Emission Spectrum of a Molybdenum Target



Braking X-Rays	Characteristic X-rays
Negative charged anode atom electron shells decelerates moving electron and induction B of its magnetic field decreases that causes, according to Maxwell's theory, the emission of electromagnetic wave (x-ray). Braking X-Rays are characterized by the continuous spectrum and short-wave limit (λ_{min})	The incident electron removes an electron *A* from an inner shell of anode atom, leaving the vacancy. The electron from upper orbit occupies the vacancy, and a γ-photon is emitted Characteristic X-Rays are characterized by the line spectrum





Energy Transformation in the X-ray Tube

$$e\Delta V = \frac{mv^2}{2} = hf + Q$$

- If Q=0, so $$E_{\max} = hf_{\max} = \frac{mv^2}{2} = e\Delta V$$
- $$\lambda_{\min} = \frac{hc}{e\Delta V}$$ where λ_{min} is the minimum wavelength emitted

In practice: $$\lambda_{min} = \frac{12.38}{\Delta V}$$

where [V] in kilovolts,
[λ_{min}]in Angstroms

The short-wave limit of x-ray spectrum defines the <u>hardness of x-ray</u>
<u>Hard radiation (low λ)</u>
<u>Soft radiation (high λ)</u>

The x-ray radiation intensity

$$I = kiV^2Z$$

where i is a current,

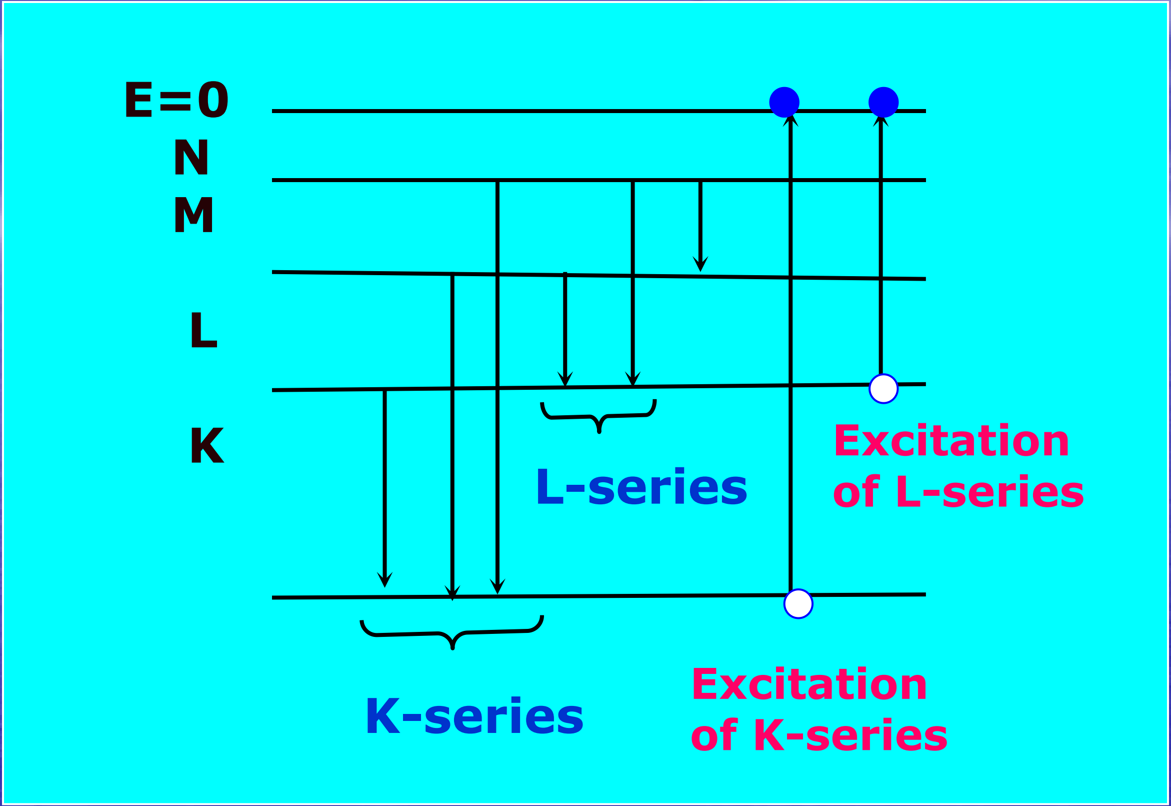
V is a voltage,

Z *is an atomic* number *of anode atom*,

k is a coefficient ($k = 10^{-9}\ V^{-1}$).

The characteristic x-rays

The inner electron shells of atom are named as K, L, M and so on.
The characteristic x-rays is composed of some spectral series named as K series, L series, M series and so on.



Moseley's law

With increasing nucleus charge the characteristic spectra move to the high frequency region:

$$\sqrt{f} = A(Z - B)$$

where f is a frequency of x-rays, Z is a ordiecutive (atomic) number of the element and A and B are constants

Law of x-ray flux loss

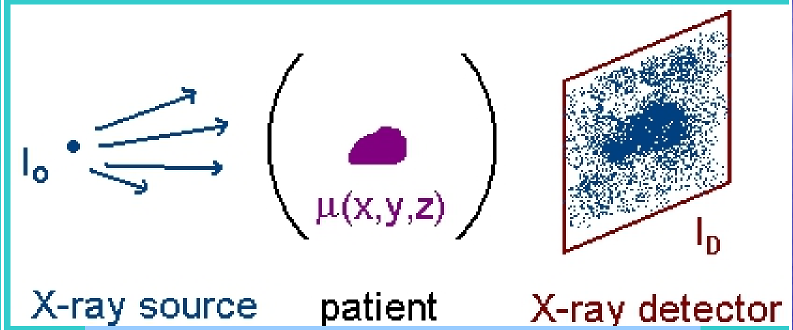
- The x-ray flux passing through a substance decreases in the following way

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

where μ is the linear attenuation coefficient, L is x-ray path.

- The linear attenuation coefficient of material increases with increasing its atomic number and density, and varies with the energy of the incident X-rays. In general μ increases with decreasing energy.
- Mass attenuation coefficient: $\mu_m = \mu / \rho$, $\mu_m = k \lambda^3 Z^3$

X-rays in medicine

Diagnostic radiology	When x-ray flux passes through the body it decreases due to the x-ray absorption by the bones (Ca) and other tissues with high atomic number (Z).	
	The pharmaceutical compounds with high x-ray attenuation coefficients for radiography are called ***Radiopaque substances*** (or radiographic contrast medium) Example: $BaSO_4$	$\mu \sim k \lambda^3 Z^3$
Therapeutic radiology	**The rapid mitosis of cancer cells made them more susceptible to radiation destruction and less capable of regeneration than slower-growing normal cells.** **X-rays can be used for killing the cancer cells without destroying an unacceptable amount of normal cells.**	

The types of ionizing radiation

Ionizing radiation is radiation that carries enough energy to ionize atoms.

EM waves: $^{0}_{0}\gamma$

- **X-rays,**
- **gamma rays**

Beams of particles:

- **alpha particles** $^{4}_{2}\alpha$
- **beta particles,** $^{0}_{-1}\beta$ $^{0}_{+1}\beta$
- **protons,**
- **neutrons.**

- **Penetration power decreases:**

  gamma-beta-alpha

- **Ionizing power decreases:**

  alpha-beta-gamma

Clinically Useful Radioisotopes

ELEMENT	RADIOISOTOPE	ACCUMULATION
iodine	${}^{131}_{53}I$	thyroid, lung, kidney
chromium	${}^{51}_{24}Cr$	spleen
selenium	${}^{75}_{24}Se$	pancreas
technetium	${}^{99m}_{43}Tc$	brain, lung, liver, spleen, bone, kidney, thyroid, heart, skeletal muscle
gallium	${}^{67}_{31}Ga$	lymphomas
hydrogen	${}^{3}_{1}H$	a variety of clinical assays

The decay law

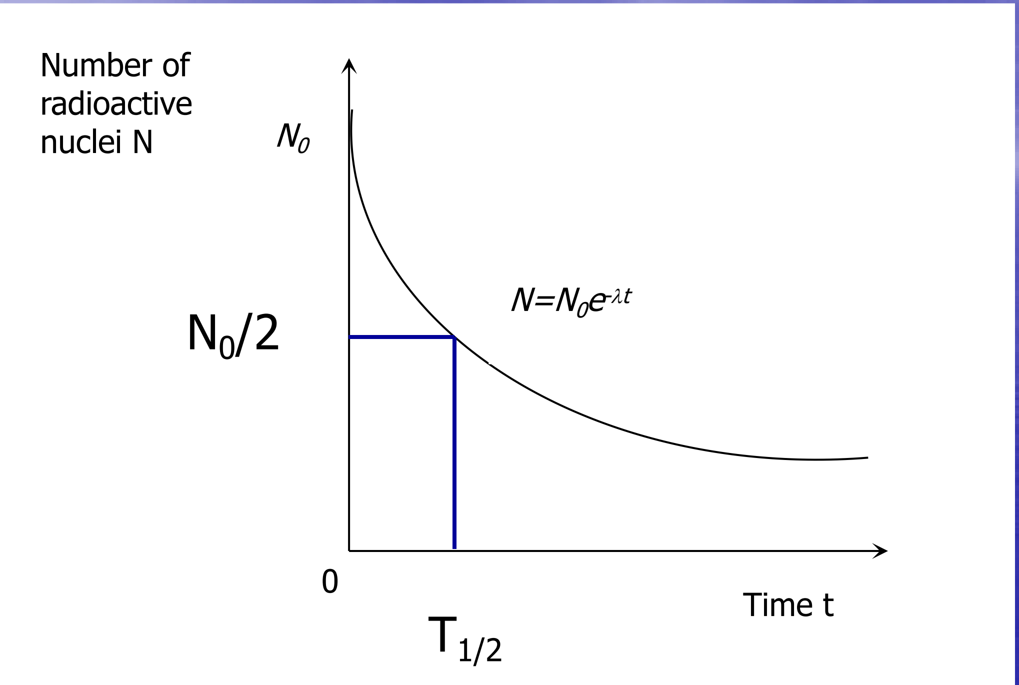
Radioactive decay is the process whereby a radioactive isotope breaks down to release radiation, nuclei and elementary particles.

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

where N_0 is the initial number of radioactive nuclei, N is the number of radioactive nuclei at the given moment, λ is a radionuclide decay constant, t is a time.

The negative sign indicates that the population of radioactive nuclei decreases with increasing time.

The half-decay period



Major radioactive substances released by the Chernobyl accident	
Iodine-131	8.02 days
Strontium-90	28.79 years
Caesium-137	30 years
Plutonium-241 (which decays into Americium-241)	14.4 years (430 years)

$$T_{1/2} = \frac{1}{\lambda}\ln 2$$

- The probability of decay is usually expressed in terms of the half-decay period (the half-life, $T_{1/2}$) rather than λ;
- The half of radioactive nuclei decays within a half-decay period (or half-life).

The activity

- The activity is a rate of decay.

$$A = -\frac{\Delta N}{\Delta t} = \lambda N_0 e^{-\lambda t} = \lambda N$$

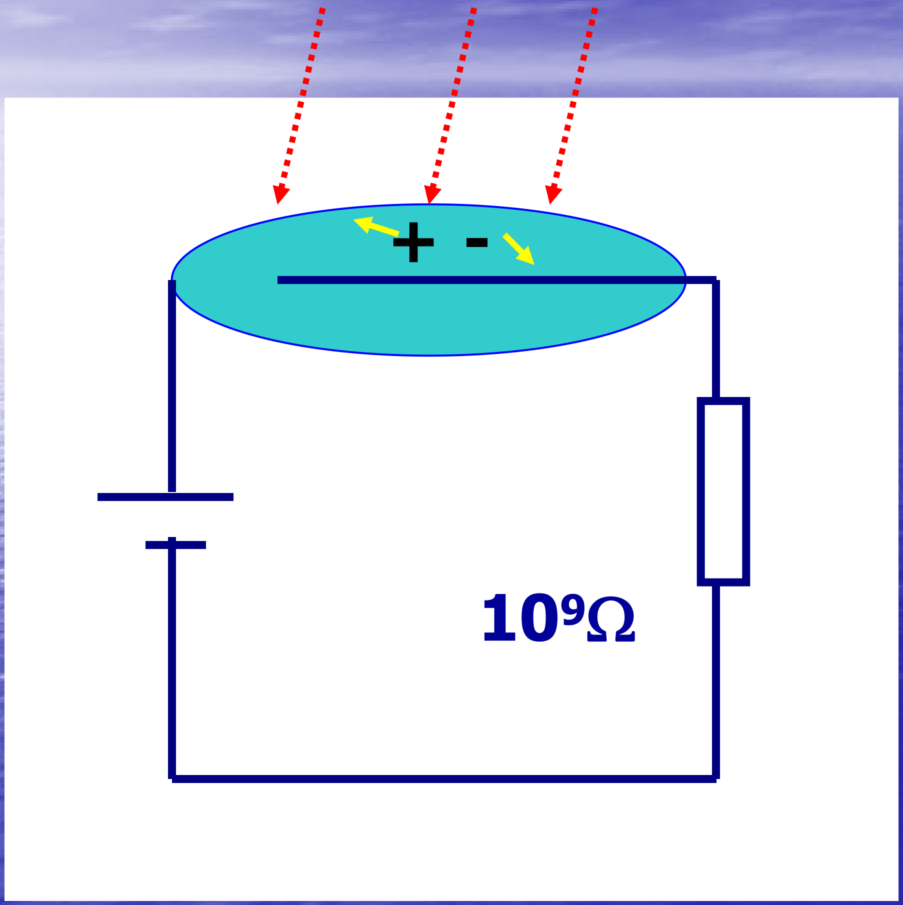
$$A = \frac{N}{T_{1/2}} \ln 2$$

- Specific activity:

$$S = \frac{A}{m}$$

The unit of the activity of radioactive sample is Becquerel (Bq).
1Bq = 1s^{-1}.
The off-system unit of activity is Curie (Ci). The activity in 1 Ci characterizes the source with decay rate in $3{,}7\times10^{10}$ disintegration/second. **1Bq= $2{,}7\times10^{-11}$Ci**.

Geiger-Mueller detector



- The Geiger counter consists of an argon-filled tube.
- Radiation enters the tube, ionizes the argon producing ion-pairs (i.e., an electron and an argon cation) that creates current.

Dosimetry deals with measuring ionizing radiation

- Absorbed dose is the energy absorbed per unit mass:
  - $D = \Delta E / \Delta m$

SI units: Gray (Gy)

1 Gray = 1 J/kg

Non-system units: rad

1 Gy=100 rad

Louis Harold Gray

Inventor of radiobiology

Exposure

- Exposure: $X=\Sigma q_i/m$, Σq_i is the total electric charge (of one sign) produced in a small volume of air of mass m
- SI units: C/kg, non-system units: 1 rontgen (R)

1C/kg=3876 R

Equivalent Dose

- $H_T = K \times D$,

where D is absorbed dose,

K is quality factor

(weighting factor for the type

of radiation or

Relative Biological Effectiveness (RBE))

SI units: Sievert, non-system units: rem

1 Sv = 100 rem

rem (roentgen equivalent in man)

Rolf Maximilian Sievert

Pioneer in studying the impact of repeated radioactivity exposure (and its application to cancer treatment)

K for various types of radiation

Type of Radiation	K
X-Ray, beta particles, electrons	1
Protons (>2 MeV)	5
Neutrons (energy dependent)	5-20
Alpha particles and other multiple-charged particles	20

Effective Dose is the summation of equivalent doses for each organ or tissue:

$$\mathbf{E = \Sigma\, H_T \times w_T,}$$

where $\mathbf{w_T}$ is weighting factor for the type of tissue, $\mathbf{H_T}$ is tissue equivalent dose.

Unit: Sievert, (Sv).

Tissue factor w_T assigned by the international commission on radiological protection

Tissue or organ	w_T
Gonads	0.20
Bone marrow (red)	0.12
Lung	0.12
Stomach	0.12
Breast	0.05
Liver	0.05
Esophagus	0.05
Thyroid	0.05
Skin	0.01

Dose Rate and Collective Dose

- Dose rate: $P_D = D/t$ (Gy/s, Sv/s, $C/(kg \times s)$)
- Collective dose: $H_c = \Sigma\, H_{Ti} \times N_i$

H_{Ti} is average dose equivalent in a given exposure group, N_i is the number of individuals in each exposure group

Biological effects of ionizing radiation

- Injury to living tissue can result from the transfer of energy to atoms and molecules in a cell.
- Ionizing radiation causes atoms and molecules to become ionized or excited.
- Ionizing radiation can produce free radicals,
  break chemical bonds,
  produce new chemical bonds and crosslinks between macromolecules,
  damage molecules that regulate vital cell processes (e.g. DNA, RNA, proteins).