Basic Nuclear Engineering 4
(原子核工学基礎第四)
(1) What is radiation?

Department of Transdisciplinary
Science and Engineering

Institute of Integrated Research
Laboratory for Zero-Carbon Energy

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Course Description and Aim

This class teaches the basics of radiation and its biological effects. It starts from the physical basis of radiation: what are alpha-ray, beta-ray, gamma-ray, X-ray etc and how their quantities are expressed. Next we learn the source and quantity of natural radiation exposure. Then we learn biological effects of radiation and its relationship to radiation dose. Finally we learn use of radiation in medical field and principles of safety use.

Time Table

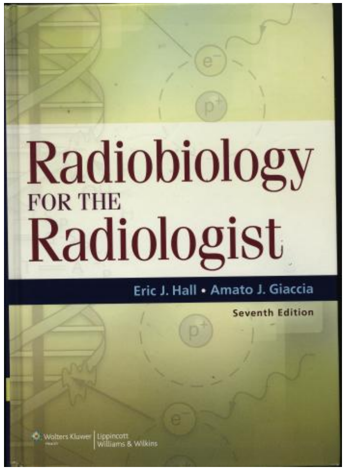
No.	Date	Contents
1	Oct 3 (Fri)	What is radiation?
2	Oct 10 (Fri)	Quantity and units of radiation, decay series, natural radiation exposure (Online)
3	Oct 17 (Fri)	Decay equilibrium, exercises
	Oct 24 (Fri)	Skip
4	Oct 31 (Fri)	Biological effects of radiation (1)
5	Nov 1 (Fri)	Biological effects of radiation (2)
	Nov 8 (Fri)	Tuesday Class
6	Nov 14 (Fri)	Therapeutic use of radiation
7	Nov 21 (Fri)	Diagnostic use of radiation, radiation protection
8	Dec 2 (Tue)	Final Examination

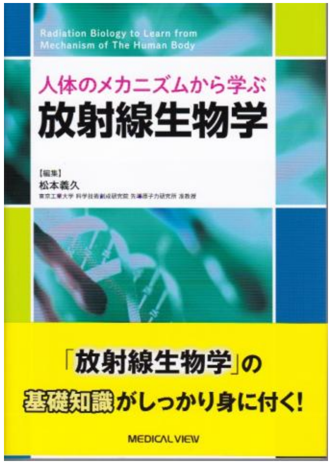
References

- Radiobiology for the Radiologist,
  7th edition
  E.J. Hall and Amato J. Giaccia
  Lippincott, Williams & Wilkins

- 新版　放射線医科学
  ―生体と放射線・電磁波・超音波―
  大西武雄監修 医療科学社

- 人体のメカニズムから学ぶ
  放射線生物学
  松本義久編 メジカルビュー社





Evaluation

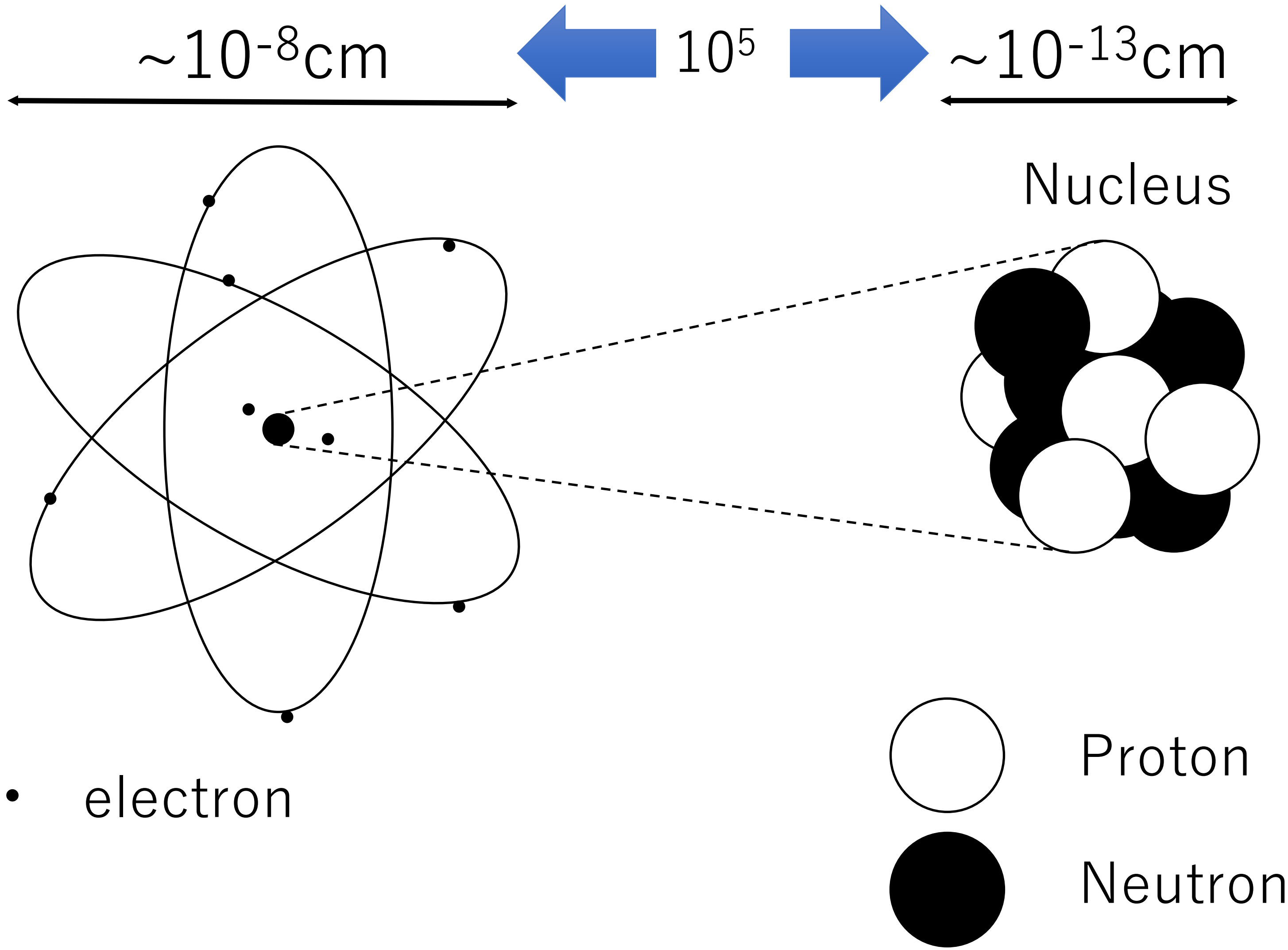
Assignments 50%

Final Examination 50%

Types of radiation

- Particle radiation
  - α -ray
  - β -ray (electron)
  - Proton
  - Heavy ion
  - Neutron
- Electromagnetic wave
  - X-ray
  - γ-ray

Structure of atom



Proton, neutron and electron

Mostly identical mass
(Neutron is slightly heavier)

Proton

Mass：1.6726×10^{-24} g
Charge：1.602×10^{-19} C

Opposite but same quantity of charge

Neutron

Mass：1.6749×10^{-24} g
Charge：None

Electron

Mass：9.1094×10^{-28} g
Charge：-1.602×10^{-19} C

Mass of electron is approximately 1/1800 of that of proton and neutron

Atomic number and mass number

Chemical properties of atom is determined by the number of electron = the number of proton
The number of neutron (N) does not matter.

↓

Atomic number (Z): the number of proton

Mass of atom is mostly determined by the sum of the number of proton and neutron
The number of electron does not matter.

↓

Mass number (A): the sum of the number of proton and neutron (N); $A=Z+N$.

Nuclide, element and isotope

Nuclide：species of atom characterized by the number of proton, the number of neutron (and nuclear energy state).

Element：nuclide of the same number of proton, i.e., the same atomic number. Denoted using specific symbol, e.g., H, which appears in the periodic table.

Isotope：nuclide of the same element with different number of neutron.

Stable isotope and radioisotope (RI)

Stable isotope：isotope, which exists stably as it is for time longer or much longer than the age of earth, solar system or universe.

Radioisotope：isotope, which is unstable and tends to change into some other nuclide more stable.
The process of change is called “decay” or “disintegration”. In every decay or disintegration, various types of radiation is emitted.

Notation of element and nuclide

$${}^{A}_{Z}X_{N}$$

X: Symbol of element
A: Mass number
Z: Atomic number
N: Number of neutron

$${}^{A}_{Z}X$$

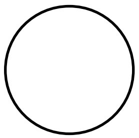
Usually “N” is omitted,
because it is know as N=A-Z

$${}^{A}X$$

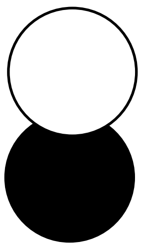
Often denoted as simple as this,
because Z is known from X

Example 1) Hydrogen isotopes

Stable isotopes

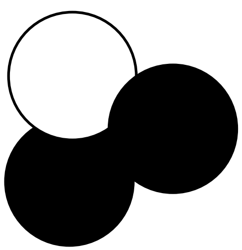


$^{1}\mathrm{H}$ $^{1}_{1}\mathrm{H}$



$^{2}\mathrm{H}$ $^{2}_{1}\mathrm{H}$ D (deuterium)

Radioisotope



$^{3}\mathrm{H}$ $^{3}_{1}\mathrm{H}$ T (tritium)

Example 2) Carbon isotopes

6 6	^{12}C	$^{12}_{6}C$	～99%
6 7	^{13}C	$^{13}_{6}C$	～1%

Stable isotopes

6 8	^{14}C	$^{14}_{6}C$	Trace
6 5	^{11}C	$^{11}_{6}C$	Not in nature Manmade

Radioisotopes

α decay (disintegration)

Mainly seen in heavy nuclides.
α ray is a high velocity helium nucleus.

$$ {}^{A}_{Z}\mathrm{X} \longrightarrow {}^{A-4}_{Z-2}\mathrm{Y} + {}^{4}_{2}\alpha $$

Examples

$$ {}^{226}_{88}\mathrm{Ra} \rightarrow {}^{222}_{86}\mathrm{Rn} + \alpha\left({}^{4}_{2}\mathrm{He}\right) $$

$$ {}^{222}_{86}\mathrm{Rn} \rightarrow {}^{218}_{84}\mathrm{Po} + \alpha $$

β^- decay (disintegration)

Seen in nuclides with excess neutrons.
A neutron changed into a proton and an electron.
β^--ray is a high speed electron.

$$ {}^{A}_{Z}\mathrm{X} \longrightarrow {}^{A}_{Z+1}\mathrm{Y} + \beta^- + \overline{\nu}_e \text{ (neutrino)} $$

Examples

$$ {}^{3}_{1}\mathrm{H} \rightarrow {}^{3}_{2}\mathrm{He} + \beta^- + \bar{\nu}_\mathrm{e} $$

$$ {}^{14}_{6}\mathrm{C} \rightarrow {}^{14}_{7}\mathrm{N} + \beta^- + \bar{\nu}_\mathrm{e} $$

β⁺ decay (disintegration)

Seen in nuclides with excess protons.
A proton changed into a neutron and a positron.
β^+-ray is positron, which is the antimatter of electron.

$$ {}^{A}_{Z}\mathrm{X} \longrightarrow {}^{A}_{Z-1}\mathrm{Y} + \beta^{+} + \nu_{e} $$

Examples

$$ {}^{11}_{6}\mathrm{C} \rightarrow {}^{11}_{5}\mathrm{B} + \beta^{+} + \nu_{e} $$

$$ {}^{18}_{9}\mathrm{F} \rightarrow {}^{18}_{8}\mathrm{O} + \beta^{+} + \nu_{e} $$

Electron capture

Seen in nuclides with excess protons.
An electron in atomic orbital is captured by a proton, which changes into a neutron.

$$^{A}_{Z}\mathrm{X} + \mathrm{e}^{-} \longrightarrow {}^{A}_{Z-1}\mathrm{Y} + \nu_{e}$$

Examples

$$^{40}_{19}\mathrm{K} + \mathrm{e}^{-} \rightarrow {}^{40}_{18}\mathrm{Ar} + \nu_{\mathrm{e}}$$

$$^{36}_{17}\mathrm{Cl} + \mathrm{e}^{-} \rightarrow {}^{36}_{16}\mathrm{S} + \nu_{\mathrm{e}}$$

γ-ray and X-ray

Both of γ-ray and x-ray are electromagnetic wave and, therefore, have similar features. They are distinguished according to the ways they are produced.

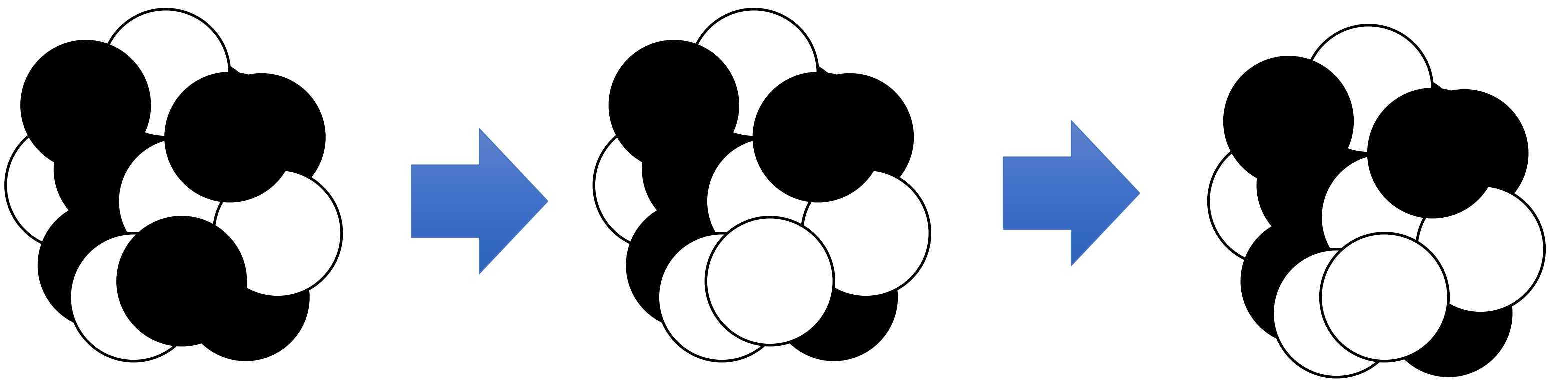
©-ray: produced *intranuclearly,*
natural

x-ray: produced *extracuclearly,*
man-made (but there is also natural)

γ-ray emission

γ-ray is emitted when the nucleus in the excited state transits to ground state or other state with lower energy, without changing the number of protons or neutrons. γ-ray emission often occurs following α-decay, β^--decay, β^+-decay or electron capture.

^{137}Cs decay: an example of γ-ray emission



^{137}Cs
Proton : 55
Neutron : 82

Unstable because of excess neutron
→A neutron tends to change into proton releasing an electron = β^{-}-ray

^{137m}Ba
Proton : 56
Neutron : 81

Still unstable with high energy
→Tends to transit to ground state by releasing energy as electro-magnetic wave = γ-ray

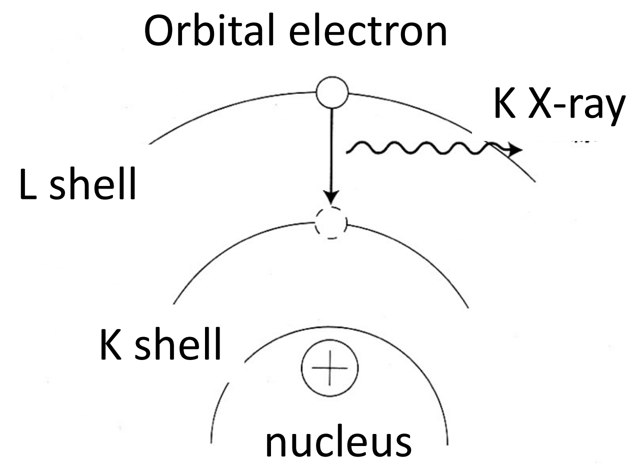
^{137}Ba
Proton : 56
Neutron : 81

Stable isotope

Two types of X-ray

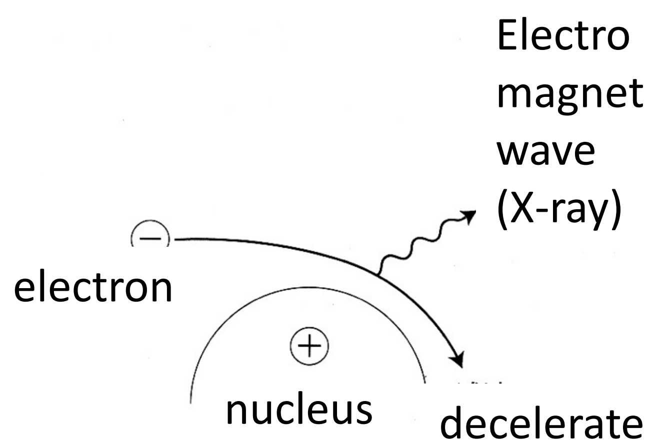
Characteristic X-ray:

Emitted when an orbital electron at an excited state transits to ground state; the energy corresponding to the difference between two status is released as electromagnetic wave.

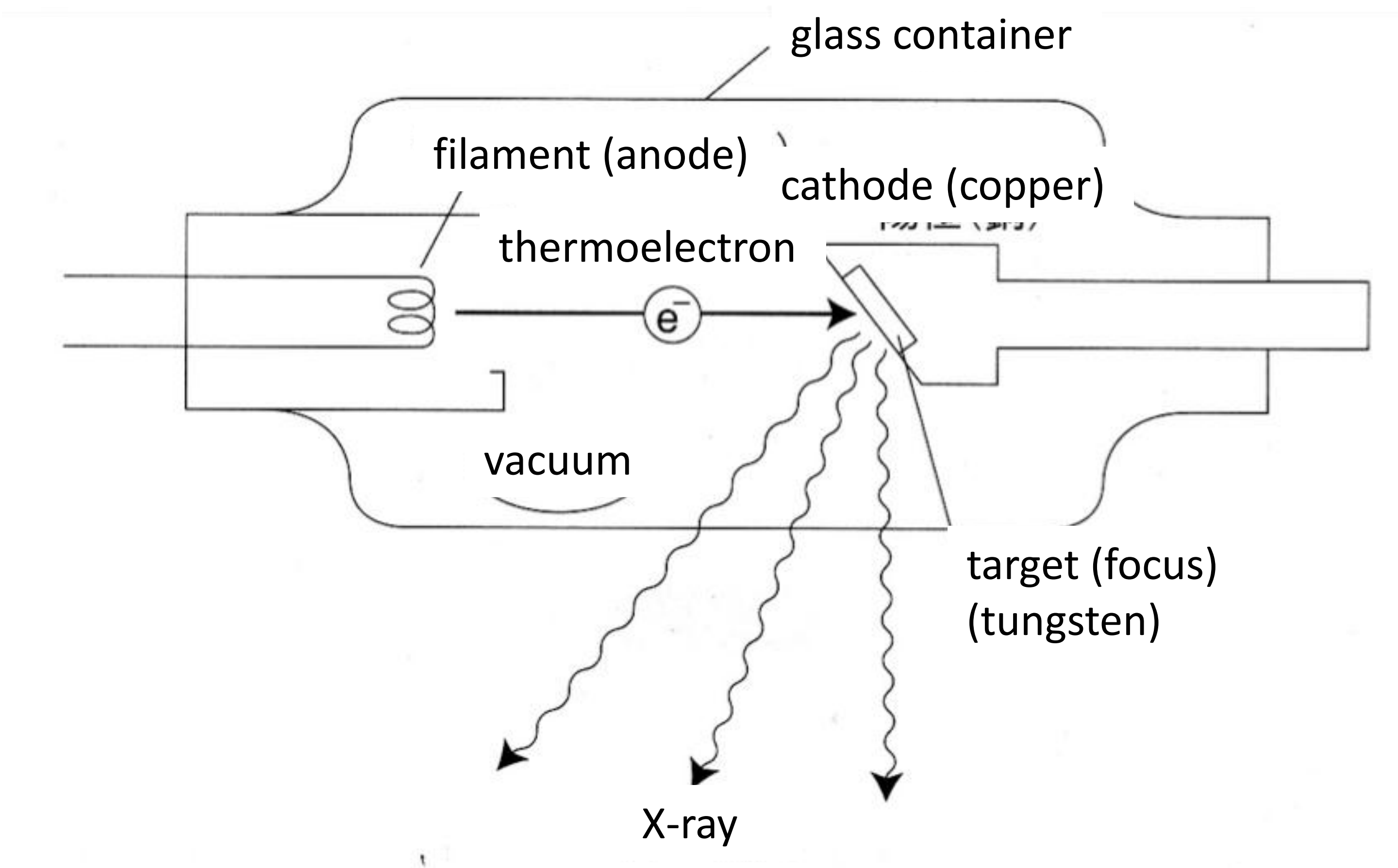


Bremsstrahlung (Braking x-ray):

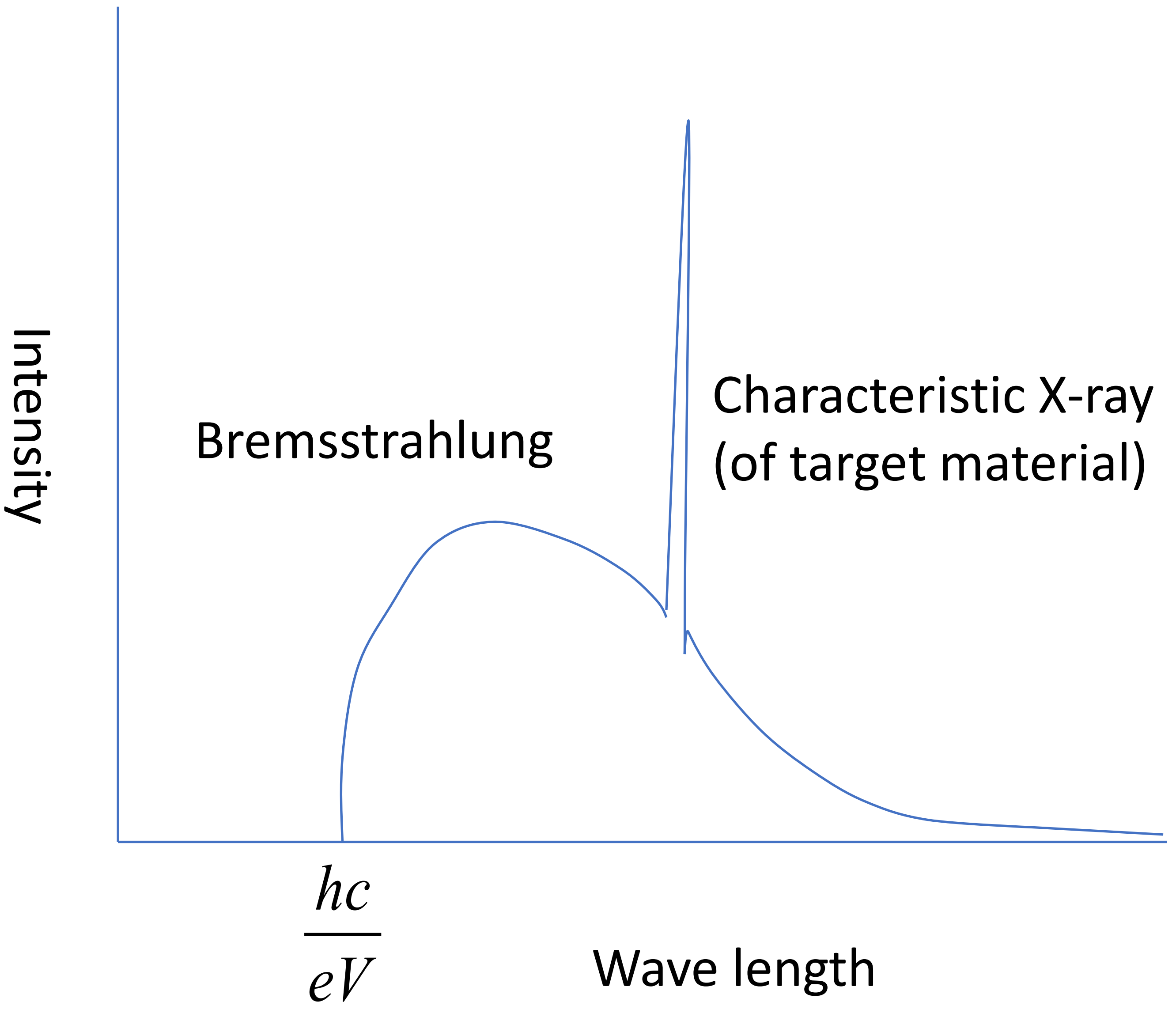
Emitted when a high speed electron is decelerated; the lost kinetic energy is released as electromagnetic wave.



X-ray generator



X-ray spectrum



Definition of “Radiation”

Flow of particles or electromagnetic wave with energies sufficient to ionize substance. Thus, also termed ionizing radiation.

(“Radiation” with lower energy, such as UV is termed “exciting radiation”)

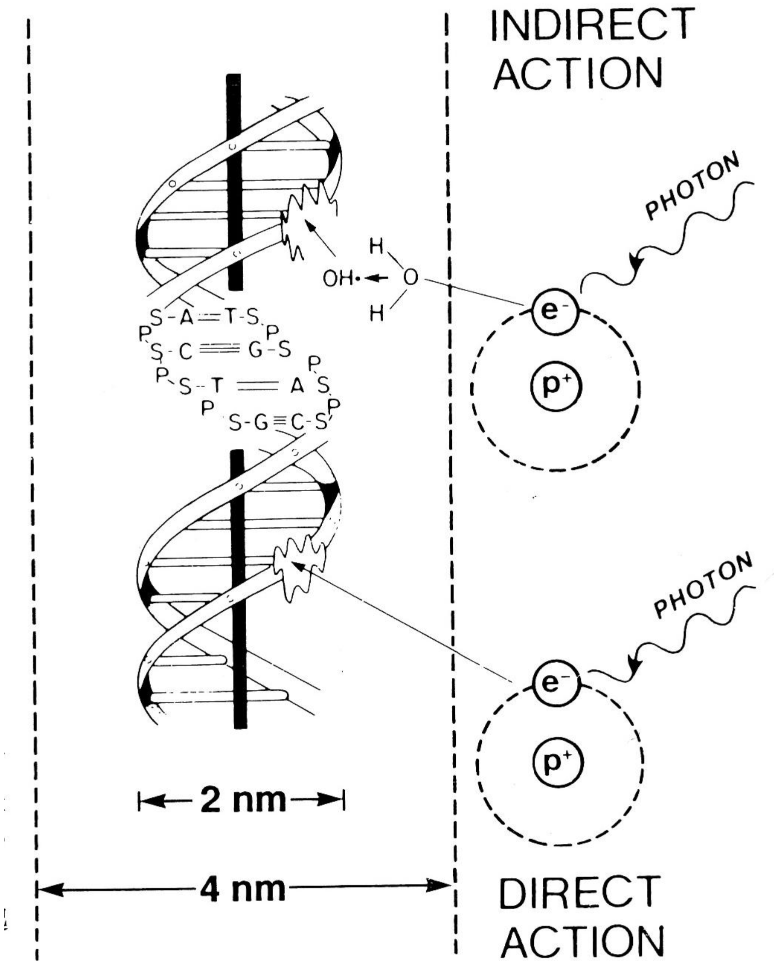
Excitation and ionization

By transferring energy to orbital electrons

Ionization ： Decompose molecule into positive and negative ions (or electron).

Excitation ： Raise energy state of electron to activated state (can transit to state different from original state)

Direct and indirect action



Direct action : Radiation directly excites or ionize the solute (DNA, here).

Indirect action : Radiation first excites or ionize the solvent (water, here) and free radical produced there reacts with the solute (DNA)

(Free) Radical

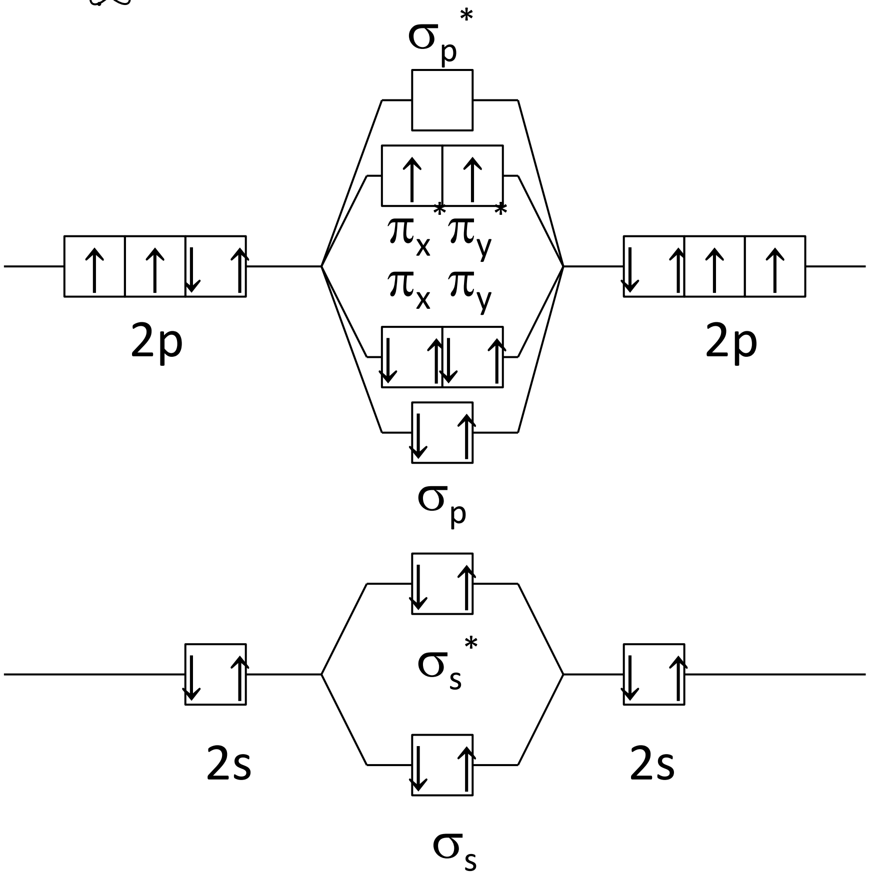
Chemical species with unpaired electron
Tend to cause electrophilic reaction
（Tend to form bond with electron and hydrogen)
↓
Radical itself: reduced
Biological molecules: oxidized
→Oxydative damages

Reactive Oxygen

Status of oxygen acquired higher reactivity than ordinary oxygen molecule (triplet oxygen) changed

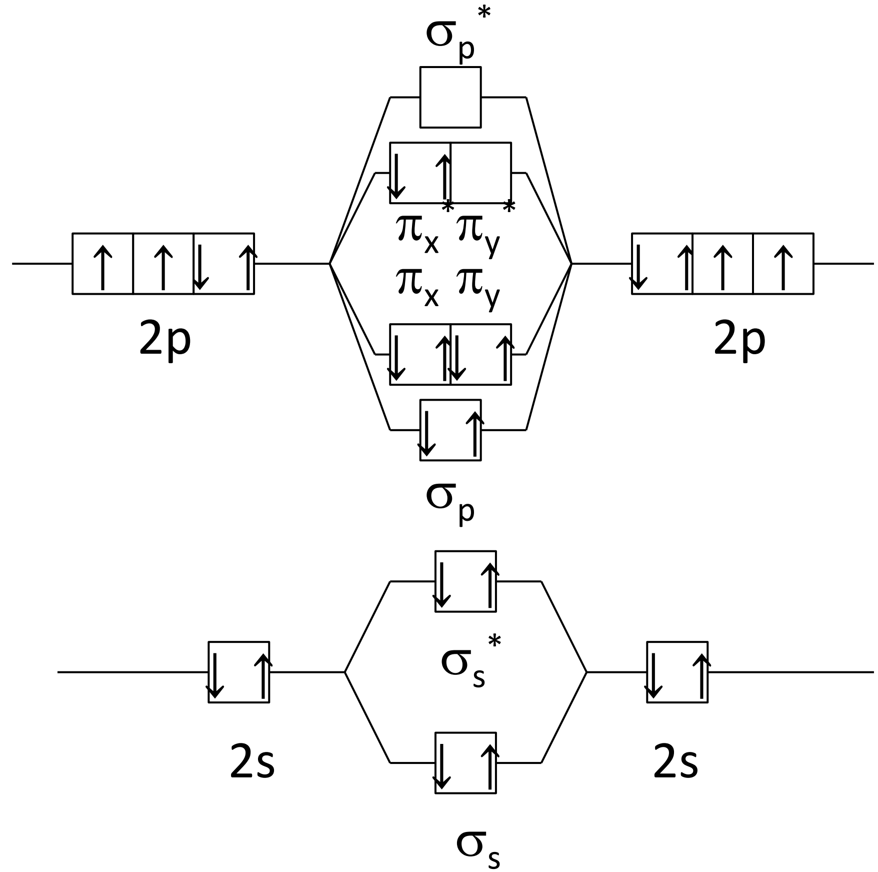
① $OH\cdot$
② $O_2^-\cdot$ (Superoxide anion radical)
③ H_2O_2
④ $^1O_2$（singlet oxygen）

Singlet oxygen and triplet oxygen



Ground state
（Triplet oxygen）

○　Radical
×　Reactive oxygen



Excited state
（Singlet oxygen）

×　Radical
○　Reactive oxygen

Generation of free radicals

1） Excitation

$$\mathrm{H_2O} \rightarrow \mathrm{H}\cdot + \underline{\mathrm{OH}\cdot}$$ （ $\mathrm{OH}\cdot$: Hydroxyl radical）

2） Ionization

$$\mathrm{H_2O} \rightarrow \mathrm{H_2O^+} + e^-$$

$$\mathrm{H_2O^+} \rightarrow \mathrm{H^+} + \underline{\mathrm{OH}\cdot}$$

$$\mathrm{H_2O^+} + \mathrm{H_2O} \rightarrow \mathrm{H_3O^+} + \underline{\mathrm{OH}\cdot}$$

$$e^- + n\mathrm{H_2O} \rightarrow e^-_{aq}$$

$$\mathrm{H_3O^+} + e^- \rightarrow \underline{\underline{\mathrm{H}}}\cdot + \mathrm{H_2O}$$

$$e^-_{aq} + \mathrm{H_2O} \rightarrow \mathrm{OH^-} + \underline{\underline{\mathrm{H}\cdot}}$$

$$e^-_{aq} + \mathrm{H^+} \rightarrow \underline{\underline{\mathrm{H}\cdot}}$$

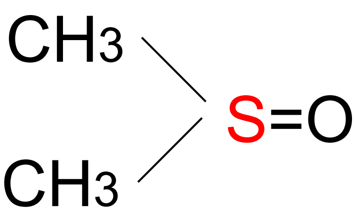
Action of radicals on biomolecules

O_2	
$\downarrow e^-$ Reduction	$\uparrow$ Oxidation
O_2^-	
$\downarrow e^-$ Reduction	$\uparrow$ Oxidation
H_2O_2	
$\downarrow e^-$ Reduction	$\uparrow$ Oxidation
$HO\cdot + H_2O$	
$\downarrow e^-$ Reduction	$\uparrow$ Oxidation
$2H_2O$	Biological molecules

Protection by radical scavenger

Radical scavenger (substance highly reactive with radical) reduces radiation effects.

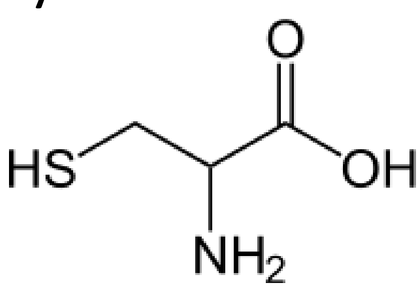
- Dimethylsulfoxide



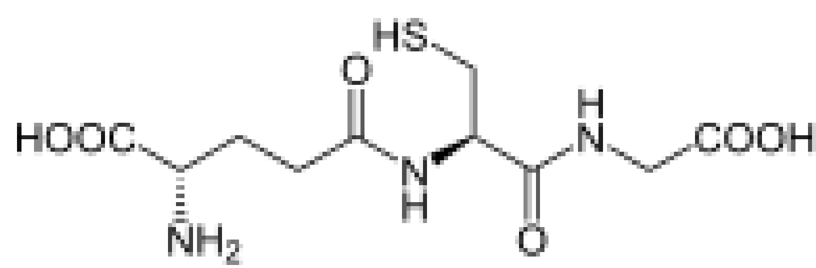
- Cysteamine

$HS\text{-}CH_2\text{-}CH_2\text{-}NH_2$

- Cystein



- Glutathione



＊Most of them have sulfur atom.