Basic Nuclear Engineering 4
(原子核工学基礎第四)
(2) How much is radiation?

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1. Radioactivity Bequerel（Bq）

Indicate “how many times radiation is emitted from radioactive substance” per second.

[Bq] = [s^{-1}]

$$\frac{dN}{dt} = -\lambda N$$ (λ: decay constant)

Named after Henri Antoine Becquerel (1852-1908, France) Nobel Prize for Physics in 1903

＊Currie （Ci）・・・Unit used before

・Radioactivity of 1 g of simple radium.

・1Ci=3.7×10^{10}Bq (1mCi=37MBq)

2. Radiation Exposure: C/kg

Indicate "how much charge is generated in the unit mass of dried air from photons, i.e., X-ray or γ-ray"

＊Roentgen (R)・・・Unit used before

・1R of radiation produces 1 esu (electrostatic unit) of charge per 1 cm^3 of air in standard temperature and pressure

・1R ≒ 2.58 X 10^{-4} C/kg: 1 C/kg ≒ 3870 R

3. Absorbed dose: Gray (Gy)

Indicate "how much energy is absorbed by the unit mass of matter from radiation" or "how much energy the radiation gives to the unit mass of matter"
=Energy per mass
[Gy] = [J/kg]

Named after Louis Harold Gray (1905-1965, UK)

4. Equivalent dose： Sievert（Sv）

Equivalent dose is the dose of radiation, taking into consideration difference in the magnitude of biological effects among various types of radiation.

Equivalent dose （Sv)
= Absorbed dose (Gy)
× Radiation Weighting Factor

Named after Rolf Maximilian Sievert (1896-1966, Sweden)

Radiation weighting factors (w_R)

Radiation	Factor	Equivalent dose for 1Gy of absorbed dose
X-ray	1	1Sv
γ-ray	1	1Sv
β-ray	1	1Sv
α-ray	20	20Sv
Neutron	2.5-21	2.5-21Sv

(ICRP Pub. 103, 2007)

Radiation Weighting Factor for Neutron

$$w_R = \begin{cases} 2.5 + 18.2\, e^{-[\ln(E_n)]^2/6}, & E_n < 1 \text{ MeV} \\ 5.0 + 17.0\, e^{-[\ln(2E_n)]^2/6}, & 1 \text{ MeV} \leqq E_n \leqq 50 \text{ MeV} \\ 2.5 + 3.25\, e^{-[\ln(0.04E_n)]^2/6}, & E_n > 50 \text{ MeV} \end{cases}$$

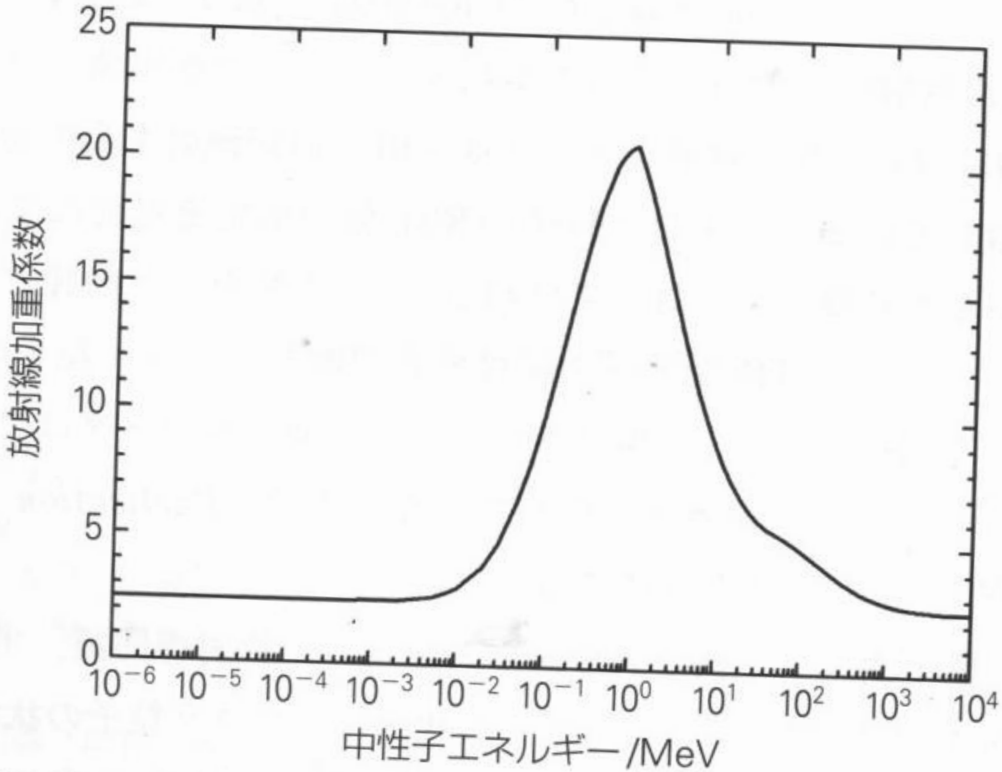
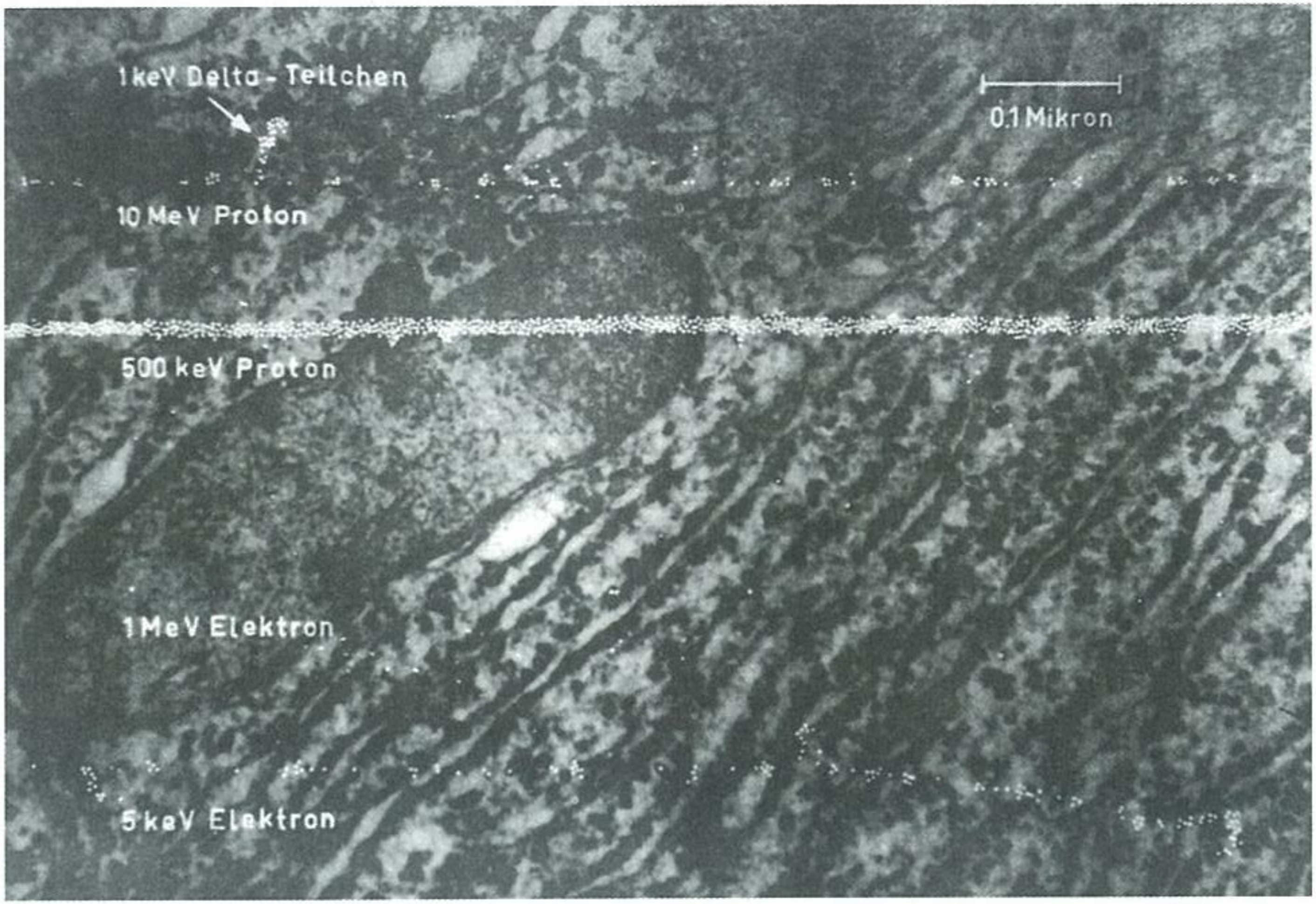


図 1　中性子に対する放射線加重係数 w_R と中性子エネルギーの関係

Density of ionization and biological effect



Dense ionization → Clustered DNA damage → Difficult to repair

5. Effective dose： Sievert（Sv)

Effective dose is the dose of radiation, taking into consideration that some parts of the body are more sensitive to radiation than others.

Effective dose （Sv)

= Σ Equivalent dose (Sv)

× Tissue Weighting Factor

"Σ" means sum of all tissues and organs in body.

Tissue weighting factors (w_T)

Tissue	Factor	Tissue	Factor
Bone marrow (red)	0.12	Liver	0.04
Colon	0.12	Thyroid gland	0.04
Lung	0.12	Bone surface	0.01
Stomach	0.12	Brain	0.01
Breast	0.12	Salivary gland	0.01
Gonads	0.08	Skin	0.01
Bladder	0.04	Other tissues	0.12
Esophagus	0.04	Total	1.00

(ICRP Pub. 103, 2007)

Ref: Tissue weighting factors (w_T) in 1990

Tissue, organ	Factor	Tissue, organ	Factor
Gonads	0.20	Liver	0.05
Bone marrow(red)	0.12	Esophagus	0.05
Colon	0.12	Thyroid gland	0.05
Lung	0.12	Skin	0.01
Stomach	0.12	Bone surface	0.01
Bladder	0.05	Other tissues	0.05
Breast	0.05	Total	1.00

(ICRP Pub.60, 1990)

Major Changes in Tissue Weighting Factors

1) Gonads: downward (0.20 -> 0.08)
←Estimates of risk for hereditary effects, which has not been detected
(Extended observation period, advance in molecular biology and human genetics)

2) Breast: upward (0.05 -> 0.12)
←Increased breast cancer 50 to 60 years after atomic bomb. Victims at young age at the time of exposure reached breast cancer susceptible age.

Decay kinetics of radioactivity

$$\frac{dN}{dt} = -\lambda N$$ (λ : decay/disintegration constant)

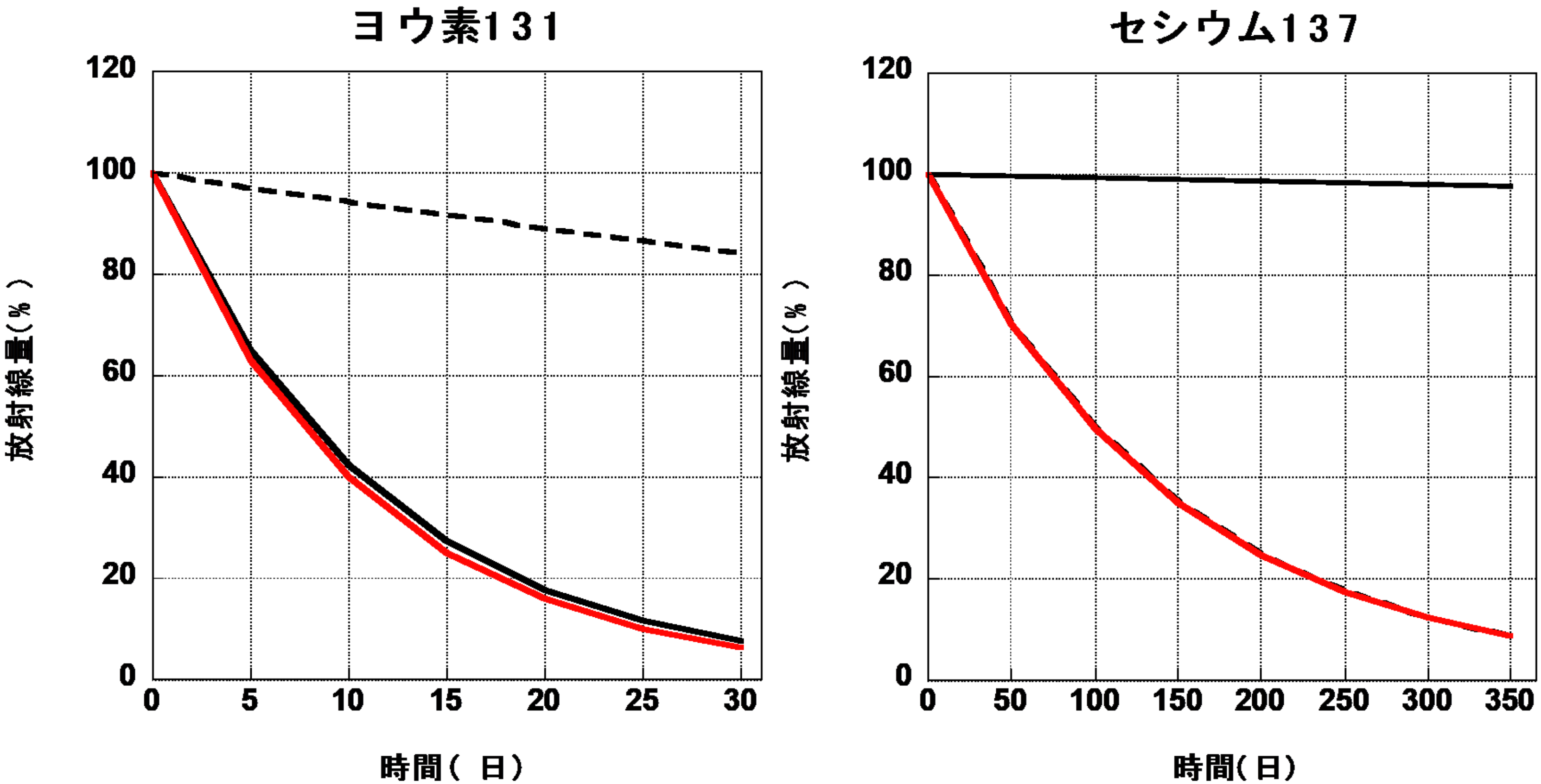
$$N = N_0 e^{-\lambda t}$$

$$N = N_0 \left(\frac{1}{2}\right)^{\frac{t}{T}}$$ (T : half life)

$$\lambda T = 0.693$$

λN = number of atom decay per second
= frequency of radiation emittion
= Radioactivity

Decrease of radioactive substance in body



: Decrease of radioactivity by decay

: Decrease of radioactivity by discharge (excretion)

: Actual decrease of radioactivity in the body

Decrease of radioactive substance in body

$$N = N_o \underbrace{\left(\frac{1}{2}\right)^{\frac{t}{T_p}}}_{\textbf{Decay}} \underbrace{\left(\frac{1}{2}\right)^{\frac{t}{T_b}}}_{\textbf{Discharge}} = N_o \left(\frac{1}{2}\right)^{\frac{t}{T_p} + \frac{t}{T_b}}$$

$$\boxed{\frac{1}{T_e} = \frac{1}{T_p} + \frac{1}{T_b}}$$

Tp: physical half-life, Tb: biological half-life
Te: effective half-life

Target organs of radioactivity

^{3}H, ^{14}C :	Whole body
^{40}K:	Whole body [Esp. muscle]
^{32}P, ^{45}Ca:	Bone (Bone component)
^{59}Fe:	Liver, Spleen(Blood component)
^{90}Sr, ^{226}Ra:	Bone (Same group as Ca)
^{131}I, ^{125}I:	Thyroid (Component of thyroid hormone)
^{134}Cs, ^{137}Cs:	Whole body [Esp. muscle] (Same group as K)
^{232}Th:	Bone, Liver (Heavy metal)
^{238}U:	Bone, Kidney(Heavy metal)

Estimation of internal exposure (1)

Dose ＝ Radioactivity × Committed effective dose coefficient

Committed effective dose coefficient (mSv/Bq)：

１） Decay, discharge and tissue distribution are considered

２） Integrated for 50 years for adults and up to 70 years for children

３） Considered as if he/she was exposed at the time of intake

Committed equivalent dose for each organ can be defined similarly

Estimation of internal exposure (2)

実効線量係数　（インターネットでも公開）：
「放射線を放出する同位元素の数量等を定める件」（平成12年科学技術庁告示第５号、最終修正　平成24年３月２８日文部科学省告示第５９号）　別表第２　第二欄、第三欄

別表第２（第７条、第１４条及び第１９条関係）
放射性同位元素の種類が明らかで、かつ、一種類である場合の空気中濃度限度等

第一欄		第二欄	第三欄	第四欄	第五欄	第六欄
放射性同位元素の種類		吸入摂取した場合の実効線量係数 (mSv/Bq)	経口摂取した場合の実効線量係数 (mSv/Bq)	空気中濃度限度 (Bq/cm^3)	排気中又は空気中の濃度限度 (Bq/cm^3)	排液中又は排水中の濃度限度 (Bq/cm^3)
核種	化学形等					
^{3}H	元素状水素	1.8×10^{-12}		1×10^{4}	7×10^{1}	
^{3}H	メタン	1.8×10^{-10}		1×10^{2}	7×10^{-1}	
^{3}H	水	1.8×10^{-8}	1.8×10^{-8}	8×10^{-1}	5×10^{-3}	6×10^{1}
^{3}H	有機物（メタンを除く）	4.1×10^{-8}	4.2×10^{-8}	5×10^{-1}	3×10^{-3}	2×10^{1}
^{3}H	上記を除く化合物	2.8×10^{-8}	1.9×10^{-8}	7×10^{-1}	3×10^{-3}	4×10^{1}
^{7}Be	酸化物、ﾊﾛｹﾞﾝ化物及び硝酸塩以外の化合物	4.3×10^{-8}	2.8×10^{-8}	5×10^{-1}	2×10^{-3}	3×10^{1}
^{7}Be	酸化物、ﾊﾛｹﾞﾝ化物及び硝酸塩	4.6×10^{-8}	2.8×10^{-8}	5×10^{-1}	2×10^{-3}	3×10^{1}
^{10}Be	酸化物、ﾊﾛｹﾞﾝ化物及び硝酸塩以外の化合物	6.7×10^{-6}	1.1×10^{-6}	3×10^{-3}	1×10^{-5}	7×10^{-1}

Estimation of internal exposure (3)

^{80}Sr	チタン酸ストロンチウム以外の化合物	1.3×10^{-7}	3.4×10^{-7}	2×10^{-1}	2×10^{-3}	2×10^{0}
^{80}Sr	チタン酸ストロンチウム	2.1×10^{-7}	3.5×10^{-7}	1×10^{-1}	8×10^{-4}	2×10^{0}
^{81}Sr	チタン酸ストロンチウム以外の化合物	3.9×10^{-8}	7.7×10^{-8}	5×10^{-1}	6×10^{-3}	1×10^{1}
^{81}Sr	チタン酸ストロンチウム	6.1×10^{-8}	7.8×10^{-8}	3×10^{-1}	3×10^{-3}	1×10^{1}
^{82}Sr	チタン酸ストロンチウム以外の化合物	3.3×10^{-6}	6.1×10^{-6}	6×10^{-3}	5×10^{-5}	1×10^{-1}
^{82}Sr	チタン酸ストロンチウム	7.7×10^{-6}	6.0×10^{-6}	3×10^{-3}	1×10^{-5}	1×10^{-1}
^{83}Sr	チタン酸ストロンチウム以外の化合物	3.0×10^{-7}	4.9×10^{-7}	7×10^{-2}	7×10^{-4}	2×10^{0}
^{83}Sr	チタン酸ストロンチウム	4.9×10^{-7}	5.8×10^{-7}	4×10^{-2}	3×10^{-4}	2×10^{0}
^{85}Sr	チタン酸ストロンチウム以外の化合物	5.6×10^{-7}	5.6×10^{-7}	4×10^{-2}	3×10^{-4}	1×10^{0}
^{85}Sr	チタン酸ストロンチウム	6.4×10^{-7}	3.3×10^{-7}	3×10^{-2}	1×10^{-4}	1×10^{0}
^{85m}Sr	チタン酸ストロンチウム以外の化合物	5.6×10^{-9}	6.1×10^{-9}	4×10^{0}	4×10^{-2}	1×10^{2}
^{85m}Sr	チタン酸ストロンチウム	7.4×10^{-9}	6.1×10^{-9}	3×10^{0}	3×10^{-2}	1×10^{2}
^{87m}Sr	チタン酸ストロンチウム以外の化合物	2.2×10^{-8}	3.0×10^{-8}	9×10^{-1}	1×10^{-2}	3×10^{1}
^{87m}Sr	チタン酸ストロンチウム	3.5×10^{-8}	3.3×10^{-8}	6×10^{-1}	6×10^{-3}	3×10^{1}
^{89}Sr	チタン酸ストロンチウム以外の化合物	1.4×10^{-6}	2.6×10^{-6}	1×10^{-2}	1×10^{-4}	3×10^{-1}
^{89}Sr	チタン酸ストロンチウム	5.6×10^{-6}	2.3×10^{-6}	4×10^{-3}	2×10^{-5}	3×10^{-1}
^{90}Sr	チタン酸ストロンチウム以外の化合物	3.0×10^{-5}	2.8×10^{-5}	7×10^{-4}	5×10^{-6}	3×10^{-2}
^{90}Sr	チタン酸ストロンチウム	7.7×10^{-5}	2.7×10^{-6}	3×10^{-4}	8×10^{-7}	3×10^{-2}
^{91}Sr	チタン酸ストロンチウム以外の化合物	2.9×10^{-7}	6.5×10^{-7}	7×10^{-2}	7×10^{-4}	1×10^{0}
^{91}Sr	チタン酸ストロンチウム	5.7×10^{-7}	7.6×10^{-7}	4×10^{-2}	3×10^{-4}	1×10^{0}
^{92}Sr	チタン酸ストロンチウム以外の化合物	1.8×10^{-7}	4.3×10^{-7}	1×10^{-1}	1×10^{-3}	2×10^{0}
^{92}Sr	チタン酸ストロンチウム	3.4×10^{-7}	4.9×10^{-7}	6×10^{-2}	5×10^{-4}	2×10^{0}

Natural radiation exposure in Japan

	Source	Effective dose (mSv/year)
External	Cosmic	0.3
	Terrestrial	0.33
Internal (Inhalation)	Radon ^{222}Rn (Indoor, Outdoor)	0.37
	Thoron ^{220}Rn (Indoor, Outdoor)	0.09
	Smoking (^{210}Pb, ^{210}Po etc.)	0.01
	Others (Uranium etc.)	0.006
Internal (Ingestion)	^{210}Pb, ^{210}Po	0.80
	^{3}H	0.0000082
	^{14}C	0.0025
	^{40}K	0.18
	Total	2.09

出典：新版　生活環境放射線(国民線量の算定)　 H23.12 (公財)原子力安全研究協会

Natural Radiation Exposure

	Terrestrial	Cosmic	Inhalation	Ingestion	
World Average	0.48	0.39	1.26	0.29	2.4 mSv/year
Japan Average	0.33	0.3	0.48	0.99	2.1 mSv/year

Other Radiation Exposure

- Chest X-ray : 0.05 mSv/time
- CT scan : 7-13 mSv/time
- Flight : 0.2 mSv/time
  (Tokyo-New York Round)
- Space station : 0.5-0.9 mSv/day

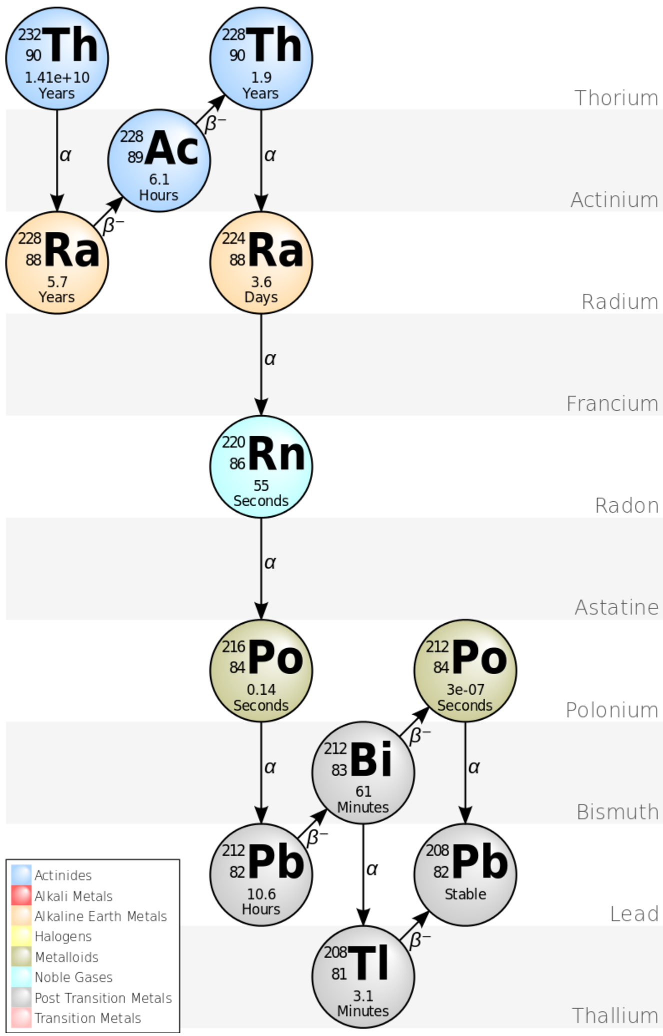
Natural radioactive nuclides

- Decay series
  1) Thorium series (4n series)
  2) Uranium series (4n+2 series)
  3) Actinium series (4n+3 series)
  4) Neptunium series (4n+1 series) --- not existent now

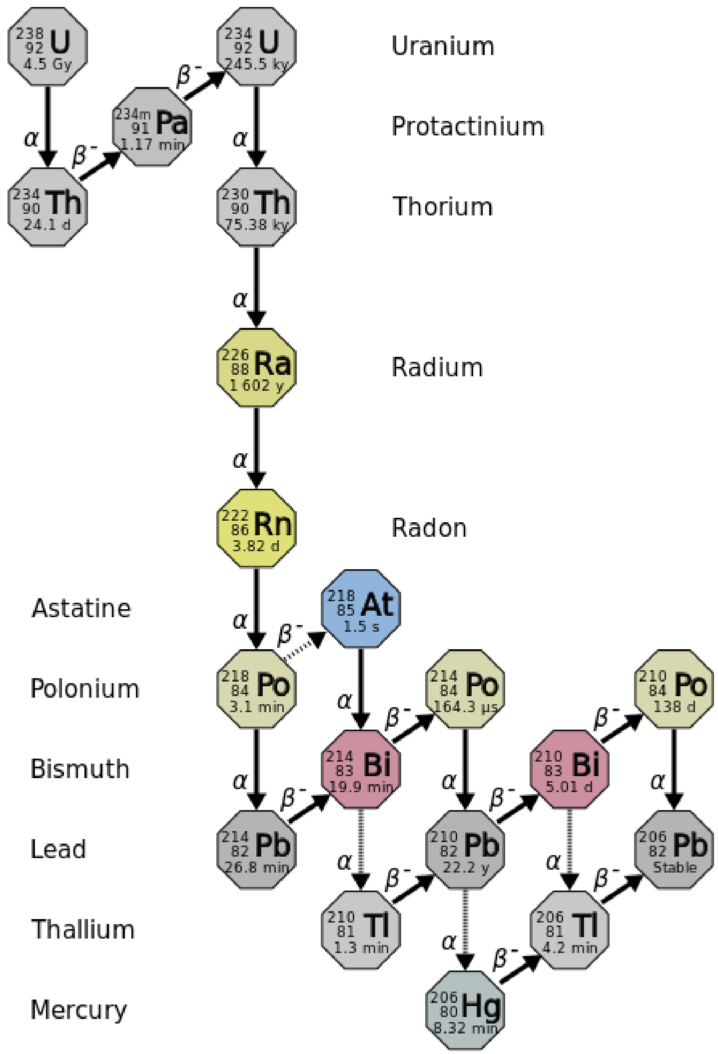
- Long-lived radioactive nuclide existent from the birth of earth
  ^{40}K (half life $1.25X10^9$ years)

- Nuclide continuously generated by cosmic ray
  ^{3}H (half life 12.3 years)
  ^{14}C (half life 5,730 years)

Natural radioactive nuclides

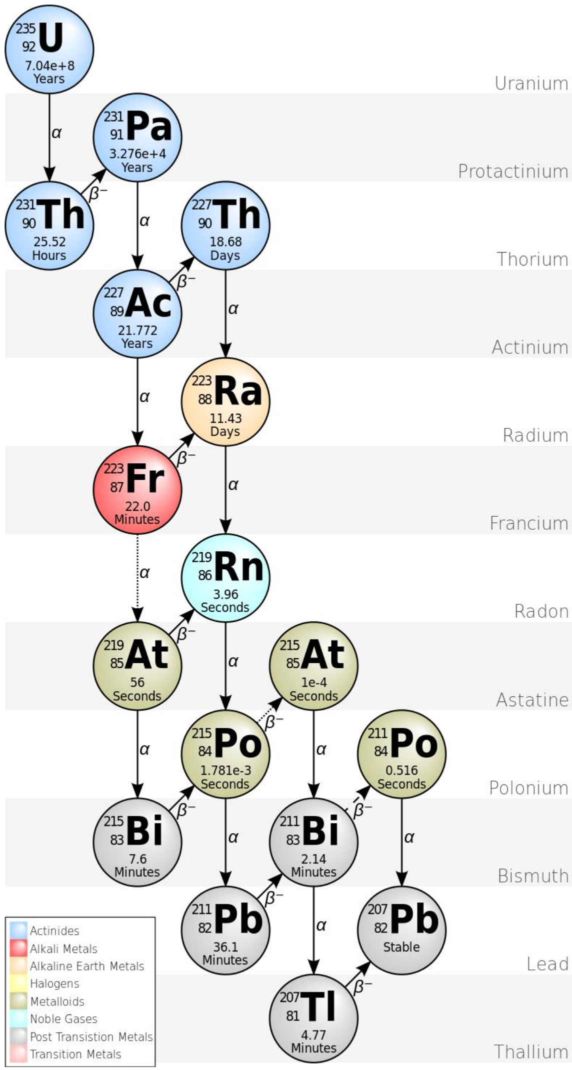


Thorium series (from Wikipedia)

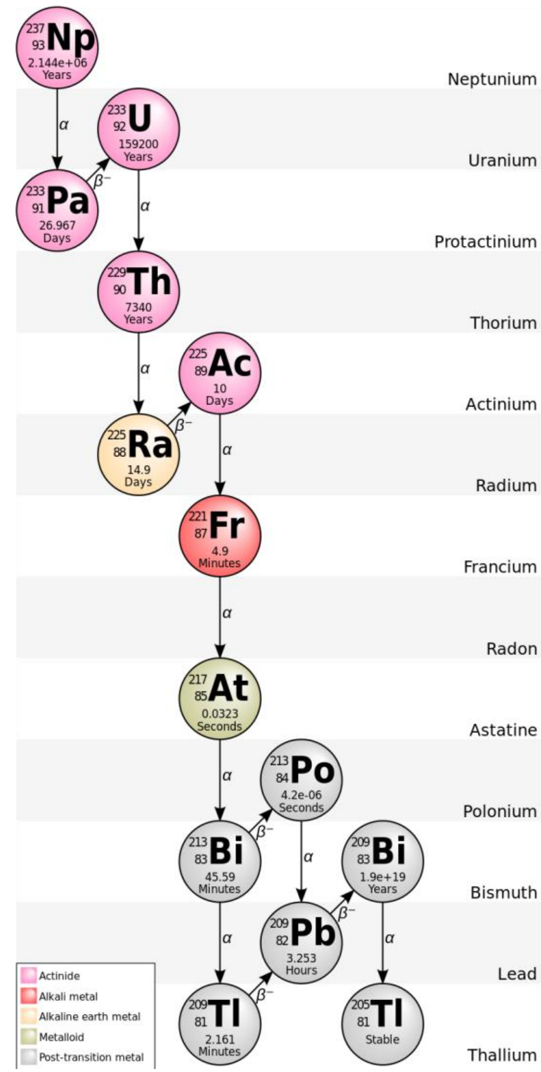


Uranium series (from Wikipedia)

Natural radioactive nuclides

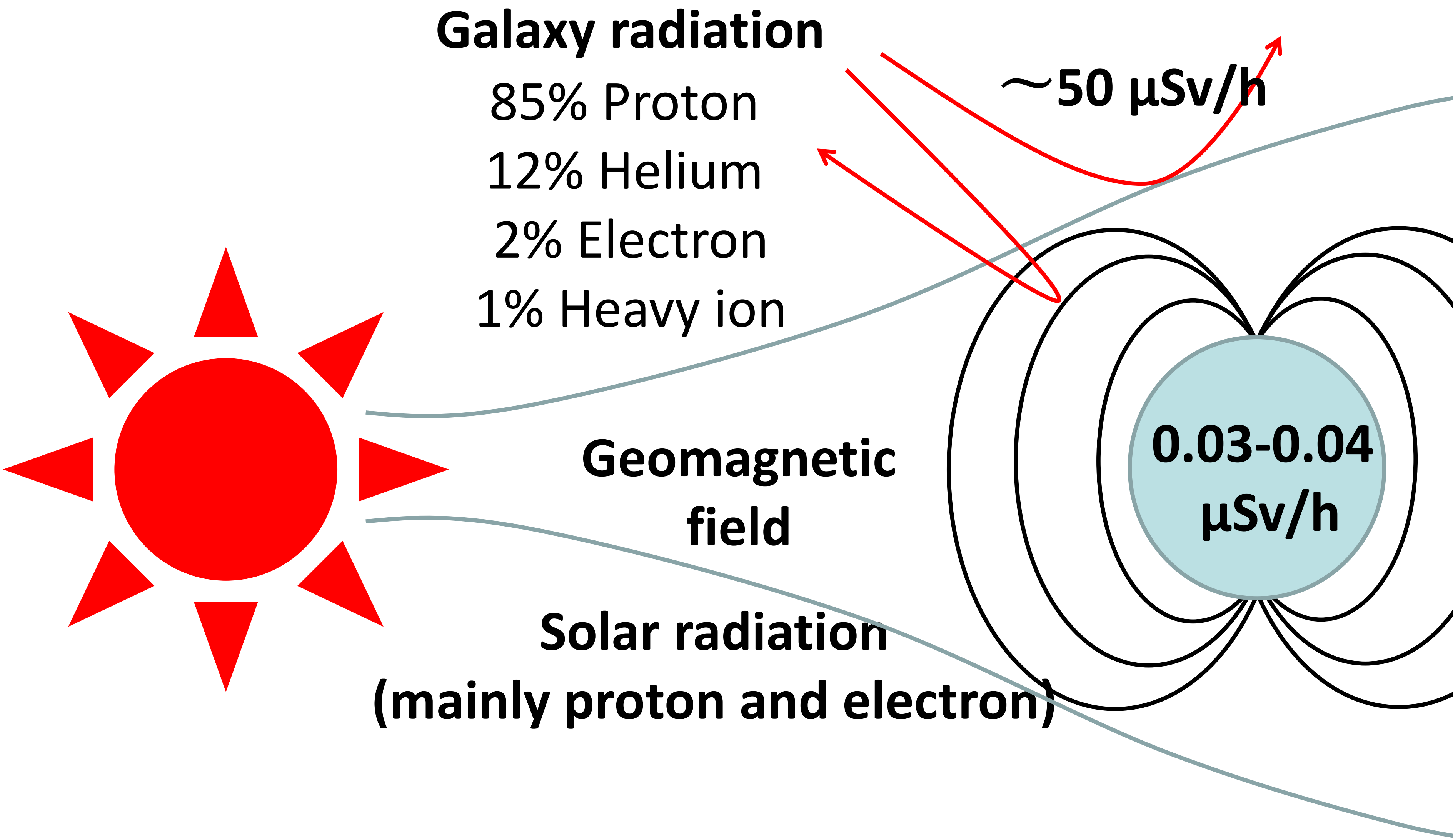


Actinium series (from Wikipedia)



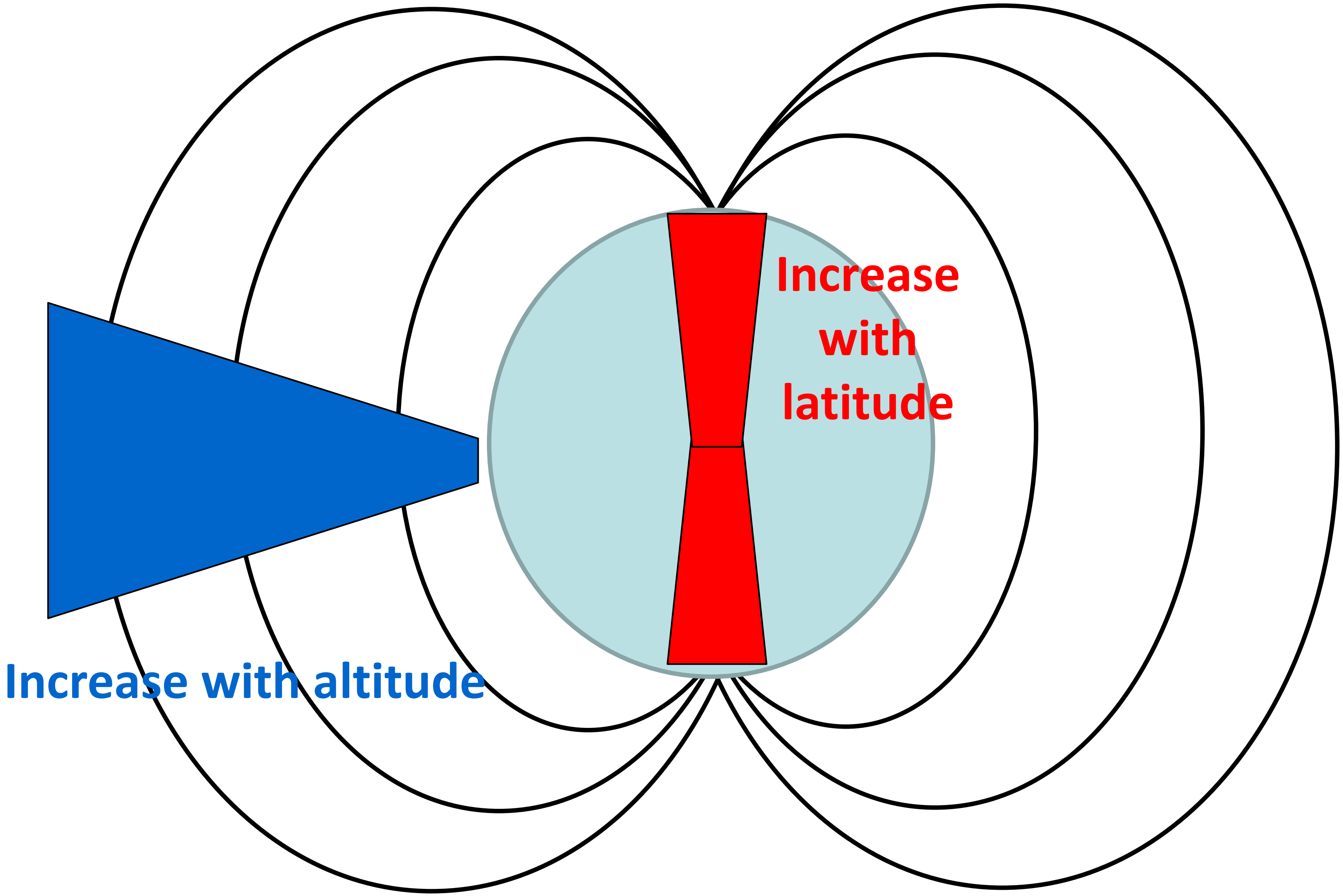
Neptunium series (from Wikipedia)

Cosmic ray



Galaxy radiation
85% Proton
12% Helium
2% Electron
1% Heavy ion
～50 µSv/h
Geomagnetic field
0.03-0.04 µSv/h
Solar radiation (mainly proton and electron)

Cosmic ray



Key to protect yourself from radiation

1. Appropriate knowledge and planning
2. Types and properties of radiation
3. Types and properties of radioactive elements and compounds