Safe Handling of Radioisotopes

—Chemistry—

Fundamental Radiochemistry

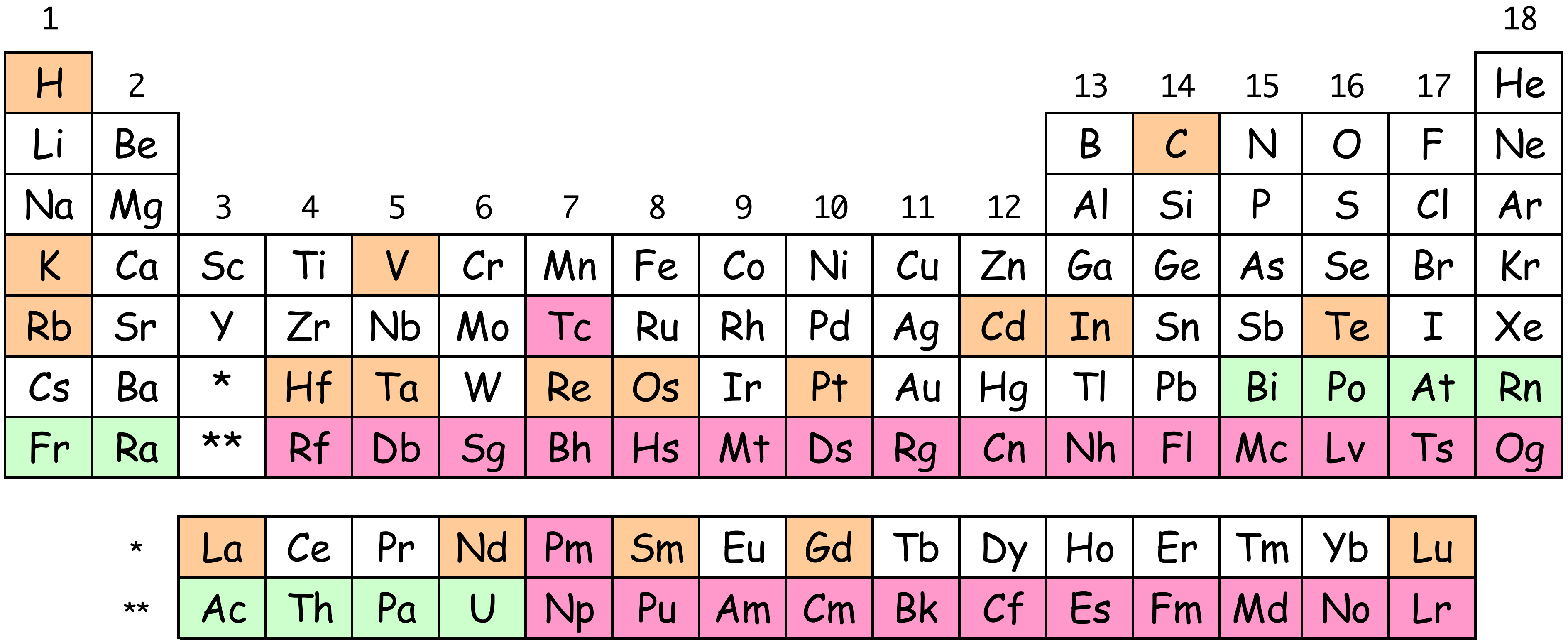
Nuclides, Radioactive decay, Decay series, Natural radionuclides,

Nuclear reactions, Radiation effect

Department of Chemistry

Yasuji Oura

令和2年度放射線業務従事者教育訓練 (2020/5/23)



1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
H																	He
Li	Be											B	C	N	O	F	Ne
Na	Mg											Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba	*	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra	**	Rf	Db	Sg	Bh	Hs	Mt	Ds	Rg	Cn	Nh	Fl	Mc	Lv	Ts	Og
	*	La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	
	**	Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr	

☐ Stable elements

🟩 Natural radioactive elements

🟧 Having natural radioactive isotopes

🟪 Artifical radioactive elements

Naming Elements 114 and 116 (2016):

Nh (Nihonium) Mc (Moscovium) Ts (Tennessine) Og (Oganesson)

Discovary of element 113 at RIKEN (2004, 2012)

^{209}Bi is a radionuclide. [(1.9±0.2)×10^{19} years] (2003)

Nuclide

Symbol of element

mass number = Z + N

$${}^{A}_{Z}\mathrm{E}_{N}$$

atomic number = number of protons

number of neutrons

Z: isotope

N: isotone

A: isobar

${}^{12}_{6}\mathrm{C}_{6}$	${}^{13}_{6}\mathrm{C}_{7}$	${}^{14}_{6}\mathrm{C}_{8}$
stable	stable	radioactive

unstable nuclides
= radionuclides

nuclides

stable nuclides

Radionuclide changes to the other nuclide spontaneously by radioactive decay.

Release energy to transfer to more stable state.

α decay

$$^{A}_{Z}\mathrm{E} \rightarrow {}^{A-4}_{Z-2}\mathrm{E}' + {}^{4}_{2}\mathrm{He}$$

α-ray

自発核分裂

neutron

β decay

$$^{A}_{Z}\mathrm{E} \rightarrow {}^{A}_{Z+1}\mathrm{E}' + \mathrm{e}^{-} + \bar{\nu}$$

$$^{A}_{Z}\mathrm{E} \rightarrow {}^{A}_{Z-1}\mathrm{E}' + \mathrm{e}^{+} + \nu$$

$$^{A}_{Z}\mathrm{E} + \mathrm{e}^{-} \rightarrow {}^{A}_{Z-1}\mathrm{E}' + \nu$$

β-ray, *γ-ray*

γ decay

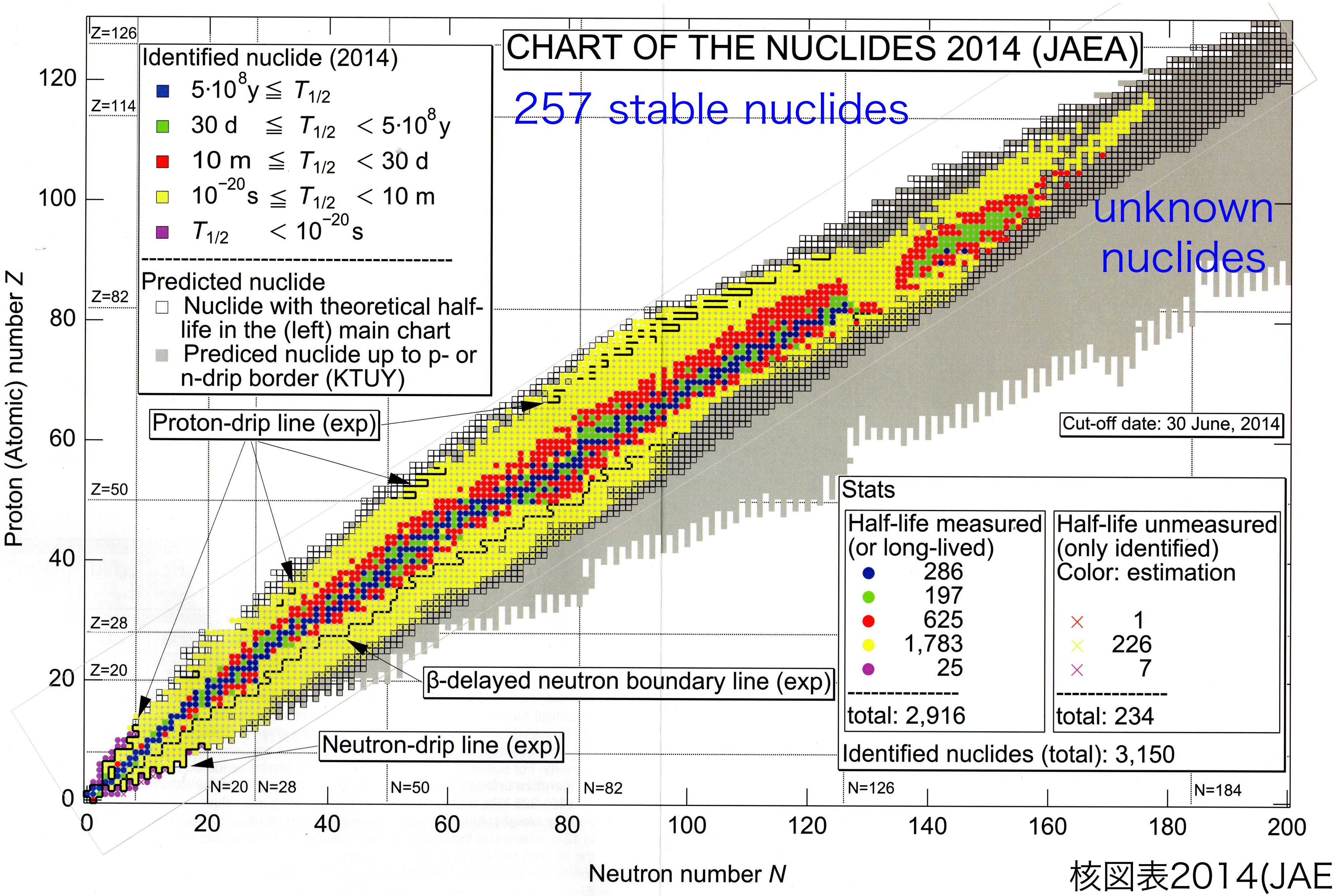
$$^{A}_{Z}\mathrm{E}^{*} \rightarrow {}^{A}_{Z}\mathrm{E} + \gamma$$

Isomeric Transition

γ-ray

conversion electron

Nuclide Chart



257 stable nuclides

unknown nuclides

核図表2014(JAEA)

Radioactive decay

probabilistic events

decay speed :

number of decaying nuclides per unit time

$$-\frac{dN}{dt} = \lambda N$$

N: number of radionuclides, λ: decay constant, t: time

⇓

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

N_0: N at t = 0

Half Life

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

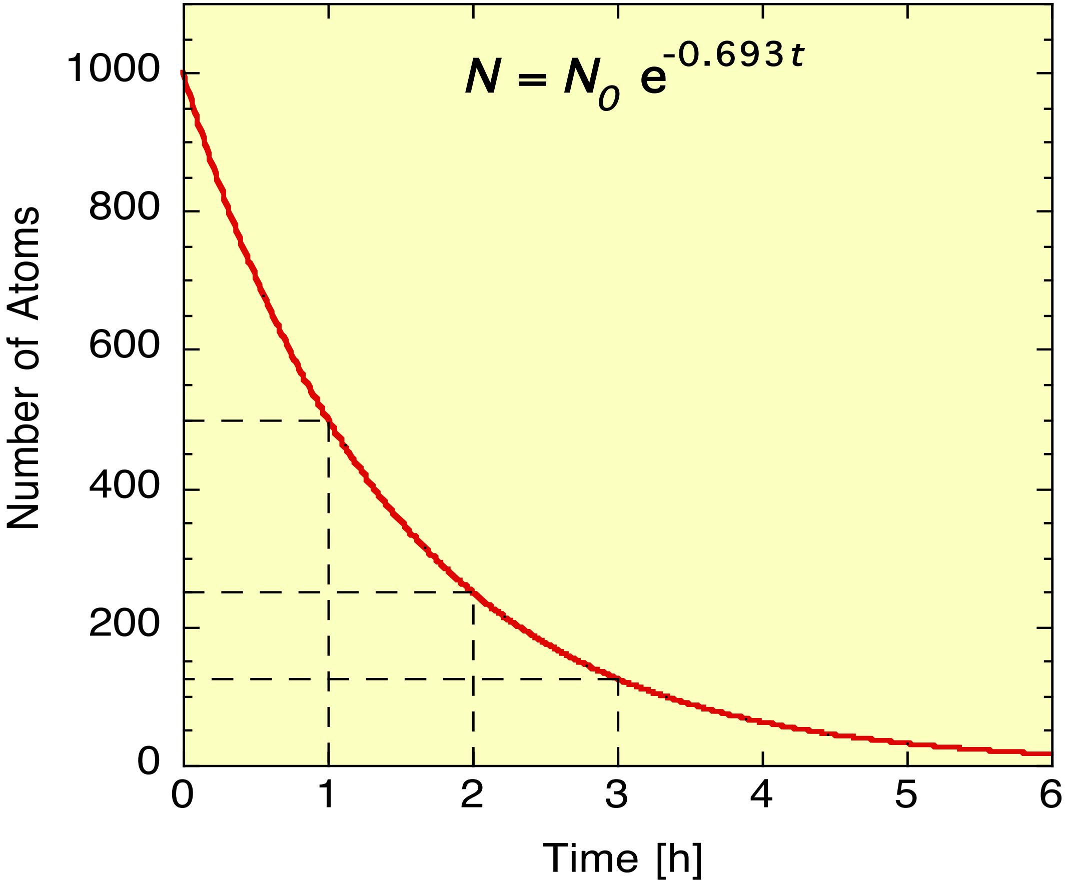
The time required for number of nuclides, $N_{0,}$ to decrease to $N_0/2$: $T_{1/2}$

$$\frac{1}{2} N_0 = N_0 e^{-\lambda T_{1/2}}$$

$$\Downarrow$$

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

$$N = N_0 \left(\frac{1}{2} \right)^{t/T_{1/2}}$$



Radioactivity

number of nuclides decaying per unit time

Unit: becquerel (**Bq**),

number of nuclides decaying a second

curie (Ci): radioactivity of 1 g of ^{226}Ra

$1\ \mathrm{Ci} = 3.7\times10^{10}\ \mathrm{Bq}$

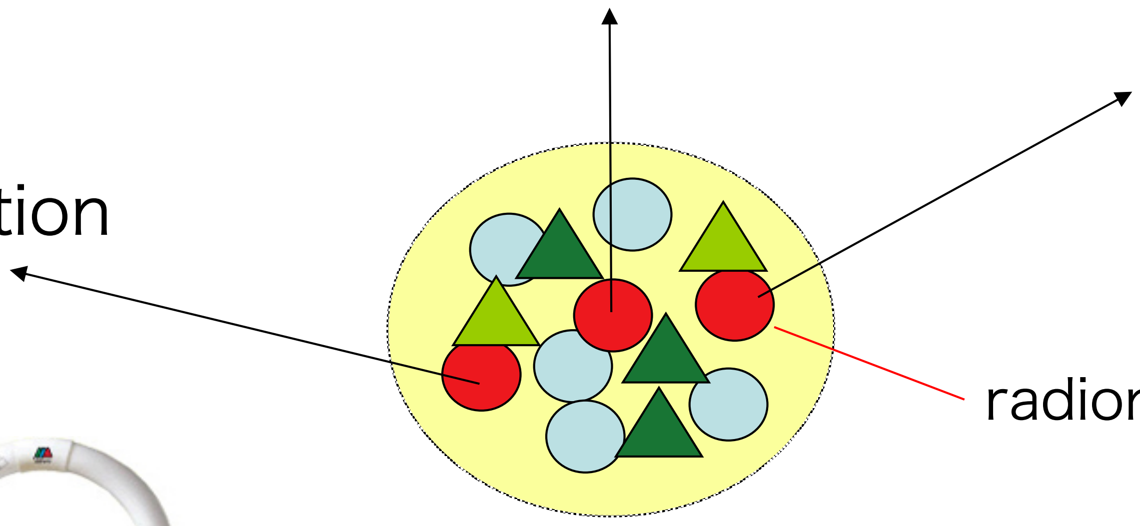
$$A = \lambda N = -dN/dt$$

A: radioactivity [Bq], λ: decay constant[s^{-1}],

N: number of nuclides

$$A = A_0 e^{-\lambda t}$$

- radioactive materials (radionuclides, materials including radionuclide(s))
- radiation
- radioactivity (amout of radionuclides, not term showing materials)



radiation

radiation

light

radiation

radioniclide

radioactive material

fluorescent lamp

Intensity: radioactivity (amount) *illuminance*

(Ex.) Radioactivity of potassium $A = \lambda N$

^{39}K : 93.3 %, ^{40}K : 0.012 %, ^{41}K : 6.7 %

$T_{1/2}$: 1.28×10^9 years

^{40}K in 1 g of K,

$$\left(\frac{0.693}{1.28\times10^{9}\times365\times24\times3600}\right)\times\left(\frac{1}{39.1}\times6.02\times10^{23}\times0.012\times10^{-2}\right)$$

$$= 32\ \mathrm{Bq}$$

K concentration in a body = 0.35 %

if weight = 60 , 6.7 kBq

32 Bq/gK

Specific radioactivity

Specific radioactivity

[Bq / g]

radioactivity per unit mass of element with its radioisotope

^{32}P :

(a) $^{31}P(n, \gamma)^{32}P$, $T_{1/2} = 14$ days

If 1 mg of P is irradiated, 60 MBq of ^{31}P is produced.

→ 6×10^4 MBq/g

(b) $^{32}S(n, p)^{32}P$, only ^{32}P = without ^{31}P [carrier-free]

60 MBq = 1.0×10^{14} atoms = 5.2×10^{-9} g

→ 1.2×10^{10} MBq/g

$$A_S = \frac{A}{W} = \frac{A}{(A/\lambda)/N_A \times M} = \frac{\lambda \times N_A}{M}$$

constant not depending on time

Specific radioactivity

[Bq / g]

radioactivity per unit mass of element with its radioisotope

Radioactivity concentration

[Bq / g, Bq / mL]

radioactivity per unit mass of material (sample) including radionuclide

^{40}K in a human body
^{137}Cs in a food

Purity

$$\text{chemical purity} = \frac{\text{amount of interested chemical species with radionuclide}}{\text{total amount of a sample}}$$

$$\text{radionuclidic purity (radiopurity)} = \frac{\text{radioactivity of a interested radionuclide}}{\text{total radioactivity in a sample}}$$

^{32}P, ^{33}P

$$\text{radiochemical purity} = \frac{\text{radioactivity of radionuclide in a specific chemical form}}{\text{total radioactivity of the radionuclide}}$$

PO_4^{3-}, PO_3^{2-}

Purity

$$\text{chemical purity} = \frac{\text{amount of interested chemical species with radionuclide}}{\text{total amount of a sample}}$$

Content of Target Element
Irrelevant radioactivity

Ex. If the weight of Cu in a 1.00 g sample containing a small amount of Ni and Zn is 0.99 g, the chemical purity is 99%.

$$\text{radionuclidic purity} = \frac{\text{radionuclide}}{\text{total radioactivity in a sample}}$$

(radiopurity)

^{32}P, ^{33}P

$$\text{radiochemical purity} = \frac{\text{radioactivity of radionuclide in a specific chemical form}}{\text{total radioactivity of the radionuclide}}$$

PO_4^{3-}, PO_3^{2-}

Purity

$$\text{chemical purity} = \frac{\text{amount of interested chemical species with radionuclide}}{\text{total amount of a sample}}$$

$$\text{radionuclidic purity} = \frac{\text{radioactivity of a interested radionuclide}}{\text{total radioactivity in a sample}}$$

(radiopurity)

^{32}P, ^{33}P

radiochemical purity =

ra

radionuclide

PO_4^{3-}, PO_3^{2-}

Ex.
^{60}Co: 100 Bq
^{137}Cs: 10 Bq
^{131}I: 90 Bq

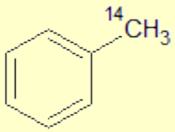
Total 200 Bq

Radionuclidic Purity of ^{60}Co
50%

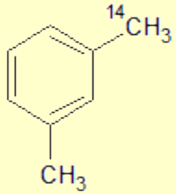
Purity

$$\text{chemical purity} = \frac{\text{amount of interested chemical species with radionuclide}}{\text{total amount of a sample}}$$

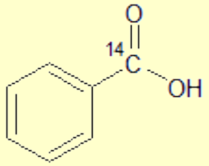
Ex.



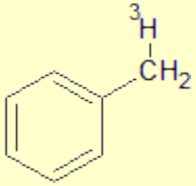
Toluene[^{14}C]
40 Bq



Xylene[^{14}C]
10 Bq



Benzoic Acid[^{14}C]
100 Bq



Toluene[^{3}H]
50 Bq

Radiochemical Purity
of Benzoic Acid [^{14}C]

$$\frac{100}{(40+10+100)} \times 100$$
$$= 66.67\%$$

P, P

$$\text{radiochemical purity} = \frac{\text{radioactivity of radionuclide in a specific chemical form}}{\text{total radioactivity of the radionuclide}}$$

PO_4^{3-}, PO_3^{2-}

Decay series

When decay products are radionuclides, decay occurs continuously. The sequence of nuclides that cause this series of decay is called decay series.

$$^{90}\text{Sr} \xrightarrow[28.7\ \text{y}]{\beta^-} {}^{90}\text{Y} \xrightarrow[64.1\ \text{h}]{\beta^-} {}^{90}\text{Zr}$$

$$^{28}\text{Al} \xrightarrow[2.3\ \text{m}]{\beta^-} {}^{28}\text{Si}$$

$$^{99}\text{Mo} \xrightarrow[66.0\ \text{h}]{\beta^-} {}^{99m}\text{Tc} \xrightarrow[6.0\ \text{h}]{\text{IT}} {}^{99g}\text{Tc} \xrightarrow[2.1\text{x}10^{5}\ \text{y}]{\beta^-} {}^{99}\text{Ru}$$

$$^{238}\text{U} \xrightarrow[4.5\text{x}10^{9}\ \text{y}]{\alpha} {}^{228}\text{Ra} \xrightarrow[5.7\ \text{y}]{\beta^-} {}^{228}\text{Ac} \xrightarrow[6.13\ \text{h}]{\beta^-} \ldots\ldots\ldots \longrightarrow {}^{212}\text{Po} \xrightarrow[0.3\,\mu\text{s}]{\alpha} {}^{208}\text{Pb}$$

parent daughter granddaughter

Radioactive Equilibrium

Decay rate of radionuclides in a decay series

$$ {}^{A_P}_{Z_P}E_P \xrightarrow[\lambda_p]{} {}^{A_D}_{Z_D}E_D \xrightarrow[\lambda_D]{} {}^{A_{GD}}_{Z_{GD}}E_{GD} $$

t = 0;	N_P^0	N_D^0	N_{GD}^0
t;	N_P	N_D	N_{GD}

$$\frac{dN_P}{dt} = -\lambda_P N_P$$

$$\frac{dN_D}{dt} = -\lambda_D N_D + \lambda_P N_P$$

Radioactive Equilibrium

$$\frac{dN_P}{dt} = -\lambda_P N_P \qquad \frac{dN_D}{dt} = \lambda_P N_P - \lambda_D N_D$$

$$\begin{cases} N_P = N_P^0 e^{-\lambda_P t} \\ N_D = \dfrac{\lambda_P}{\lambda_D - \lambda_P} N_P^0 \left(e^{-\lambda_P t} - e^{-\lambda_D t} \right) + N_D^0 e^{-\lambda_D t} \end{cases}$$

multiply λ_P or λ_D on both sides

$$\begin{cases} A_P = A_P^0 e^{-\lambda_P t} \\ A_D = \dfrac{\lambda_D}{\lambda_D - \lambda_P} A_P^0 \left(e^{-\lambda_P t} - e^{-\lambda_D t} \right) + A_D^0 e^{-\lambda_D t} \end{cases}$$

Radioactive Equilibrium

$$\begin{cases} A_P = A_P^0 e^{-\lambda_P t} \\ A_D = \dfrac{\lambda_D}{\lambda_D - \lambda_P} A_P^0 \left(e^{-\lambda_P t} - e^{-\lambda_D t} \right) + A_D^0 e^{-\lambda_D t} \end{cases}$$

1) $\lambda_P < \lambda_D$ $\left[T_{1/2}^P > T_{1/2}^D \right]$

2) $\lambda_P << \lambda_D$ $\left[T_{1/2}^P >> T_{1/2}^D \right]$

3) $\lambda_P > \lambda_D$ $\left[T_{1/2}^P < T_{1/2}^D \right]$

where $A_D^0 = 0$

1) $\lambda_P < \lambda_D$

$$\left[T^P_{1/2} > T^D_{1/2}\right]$$

$$\begin{cases} A_P = A_P^0 e^{-\lambda_P t} \\ A_D = \dfrac{\lambda_D}{\lambda_D - \lambda_P} A_P^0 \left(e^{-\lambda_P t} - e^{-\lambda_D t}\right) \end{cases}$$

After enough time, $e^{-\lambda_P t} >> e^{-\lambda_D t}$

$$A_D \approx \frac{\lambda_D}{\lambda_D - \lambda_P} A_P^0 e^{-\lambda_P t} = \boxed{\frac{\lambda_D}{\lambda_D - \lambda_P} A_P}$$

$$\frac{A_D}{A_P} = \frac{\lambda_D}{\lambda_D - \lambda_P}$$

Radioactivity ratio of daughter to parent nuclides is equal.

‖

transient equilibrium

Ex.) $${}^{99}\mathrm{Mo} \xrightarrow[66.0\ \mathrm{h}]{\beta^-} {}^{99m}\mathrm{Tc} \xrightarrow[6.0\ \mathrm{h}]{\mathrm{IT}} {}^{99g}\mathrm{Tc} \xrightarrow[2.1\mathrm{x}10^5\ \mathrm{y}]{\beta^-} {}^{99}\mathrm{Ru}$$

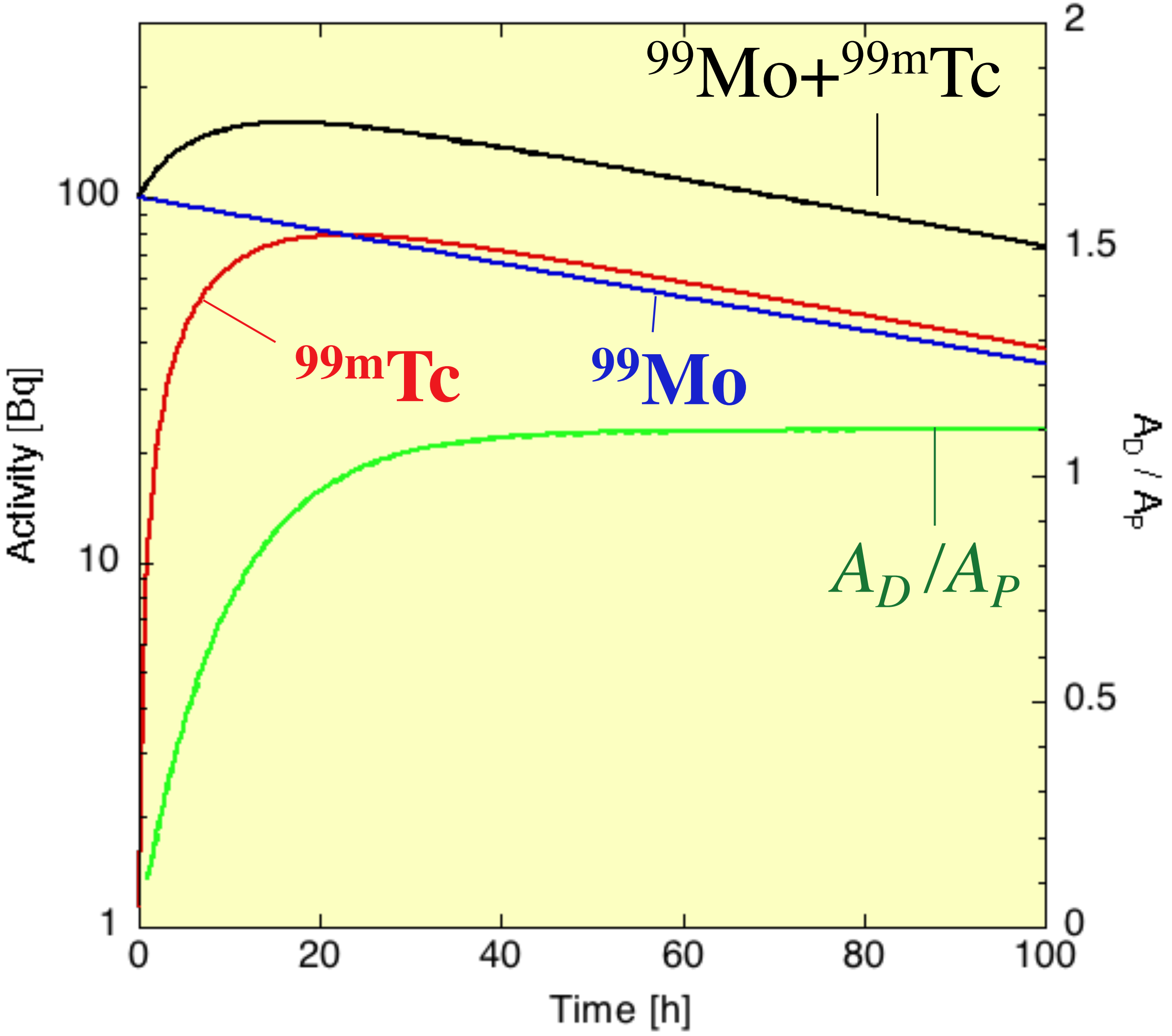
Transient Equilibrium

$$^{99}\text{Mo} \xrightarrow[66.0\text{ h}]{\beta^-} {}^{99m}\text{Tc} \xrightarrow[6.0\text{ h}]{\text{IT}} {}^{99g}\text{Tc}$$

$$\frac{A_D}{A_P} = \frac{\lambda_D}{\lambda_D - \lambda_P}$$

In the case of $^{99}\text{Mo} \rightarrow {}^{99m}\text{Tc}$,

$A_D/A_P = 1.1$



2) $\lambda_P << \lambda_D$ $\left[T_{1/2}^{P} >> T_{1/2}^{D}\right]$

$$\begin{cases} A_P = A_P^0 e^{-\lambda_P t} \\ A_D = \dfrac{\lambda_D}{\lambda_D - \lambda_P} A_P^0 \left(e^{-\lambda_P t} - e^{-\lambda_D t}\right) \end{cases}$$

After enough time, $e^{-\lambda_P t} >> e^{-\lambda_D t}$. And, $\lambda_D - \lambda_P \approx \lambda_D$

$$A_D \approx \frac{\lambda_D}{\lambda_D - \lambda_P} A_P^0 e^{-\lambda_P t} = \frac{\lambda_D}{\lambda_D - \lambda_P} A_P \approx \frac{\lambda_D}{\lambda_D} A_P$$

$$A_D = A_P$$

Radioactivity of parent and daughter nuclides are equal.

‖

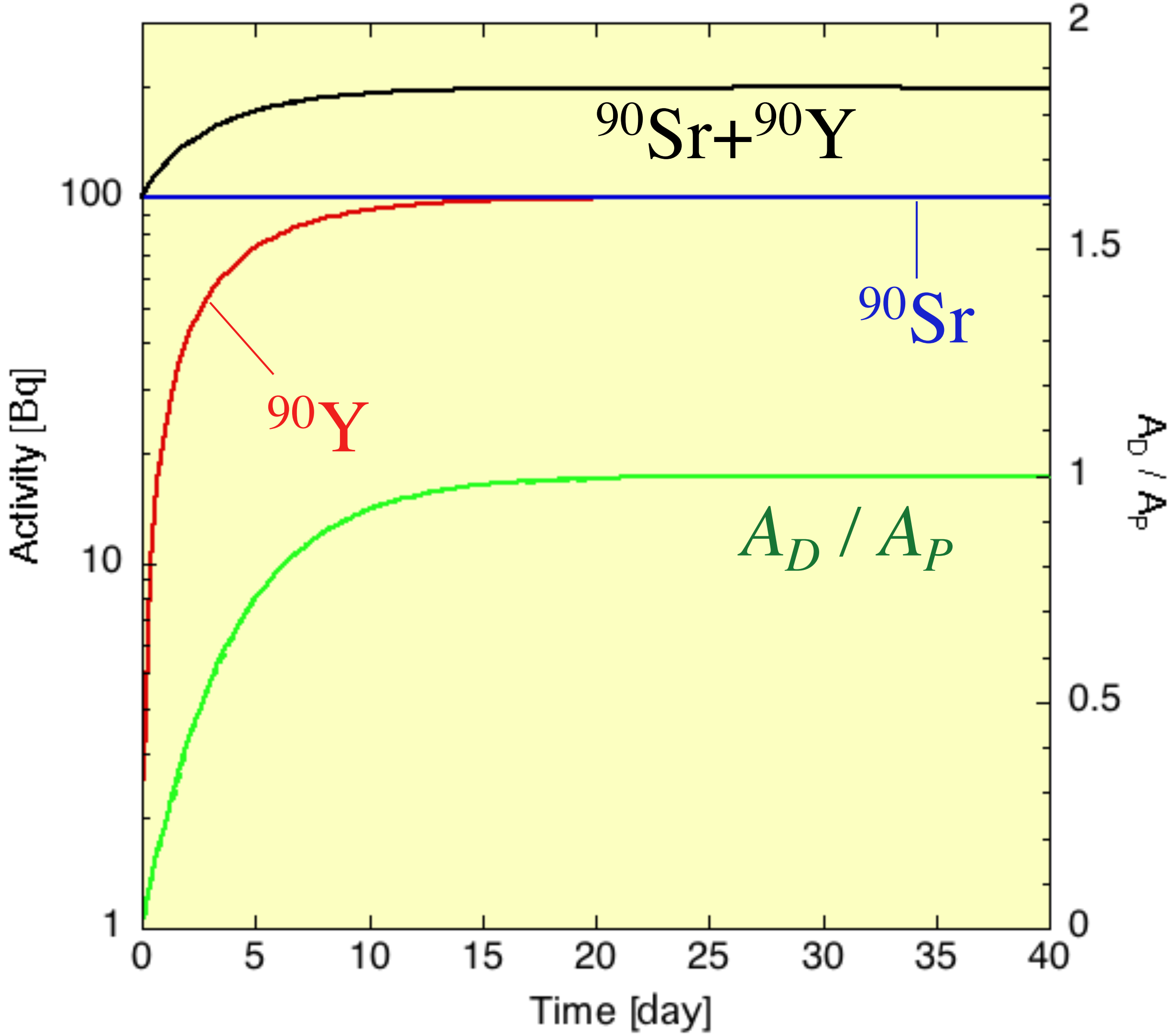
secular equilibrium

Ex.) $^{90}\mathrm{Sr} \xrightarrow[28.7\ \mathrm{y}]{\beta^-} {}^{90}\mathrm{Y} \xrightarrow[64.1\ \mathrm{h}]{\beta^-} {}^{90}\mathrm{Zr}$

Secular Equilibrium

$$A_D = A_P$$

$$^{90}\mathrm{Sr} \xrightarrow[28.7\ \mathrm{y}]{\beta^-} {}^{90}\mathrm{Y} \xrightarrow[64.1\ \mathrm{h}]{\beta^-} {}^{90}\mathrm{Zr}$$

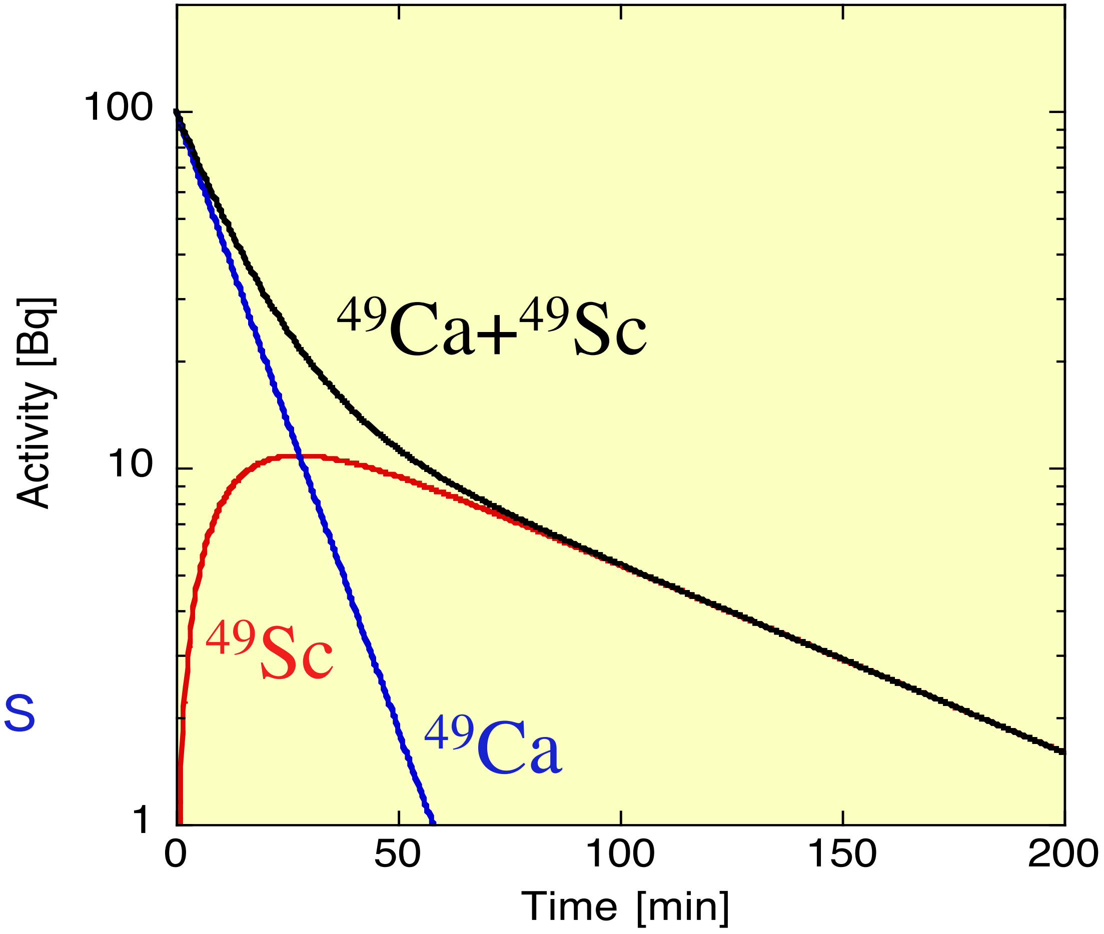


3) $\lambda_P > \lambda_D$

$$\left[T_{1/2}^{P} < T_{1/2}^{D}\right]$$

$$\begin{cases} A_P = A_P^0 e^{-\lambda_P t} \\ A_D = \dfrac{\lambda_D}{\lambda_D - \lambda_P} A_P^0 \left(e^{-\lambda_P t} - e^{-\lambda_D t}\right) \end{cases}$$

$$^{49}\text{Ca} \xrightarrow[8.7\ \text{m}]{\beta^-} {}^{49}\text{Sc} \xrightarrow[57.2\ \text{m}]{\beta^-} {}^{48}\text{Ti}$$

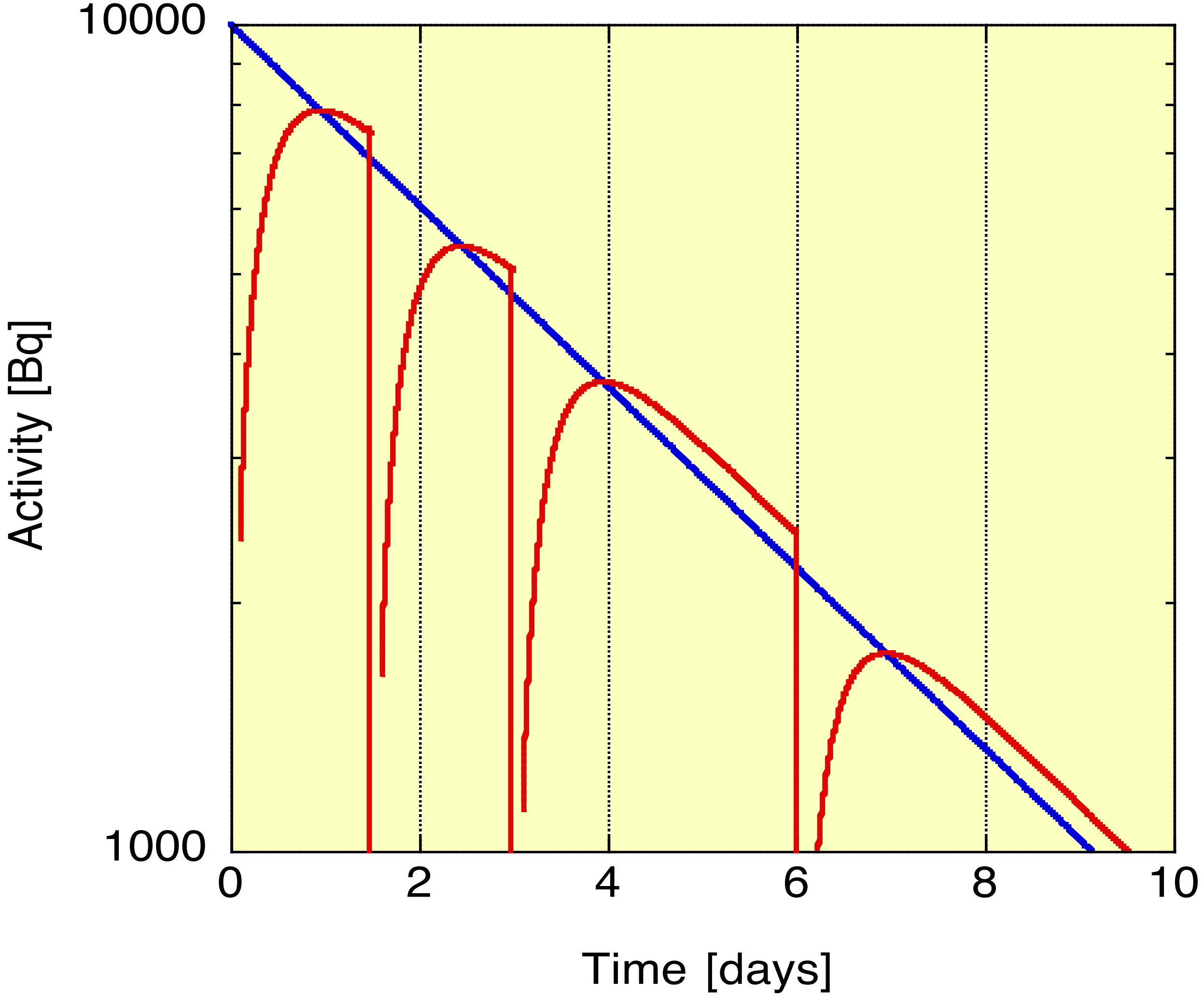


Radioactive equilibrium is not established.

Milking

Using radioactive equilibrium, daughter nuclide that is produced from parent nuclide is extracted repeatedly.

^{99}Mo(66 h) → ^{99m}Tc (6h)



Tc generator

important in nuclear medicine

Tc generator

http://fri.fujifilm.co.jp/med/products/diagnosis/brain/utk/

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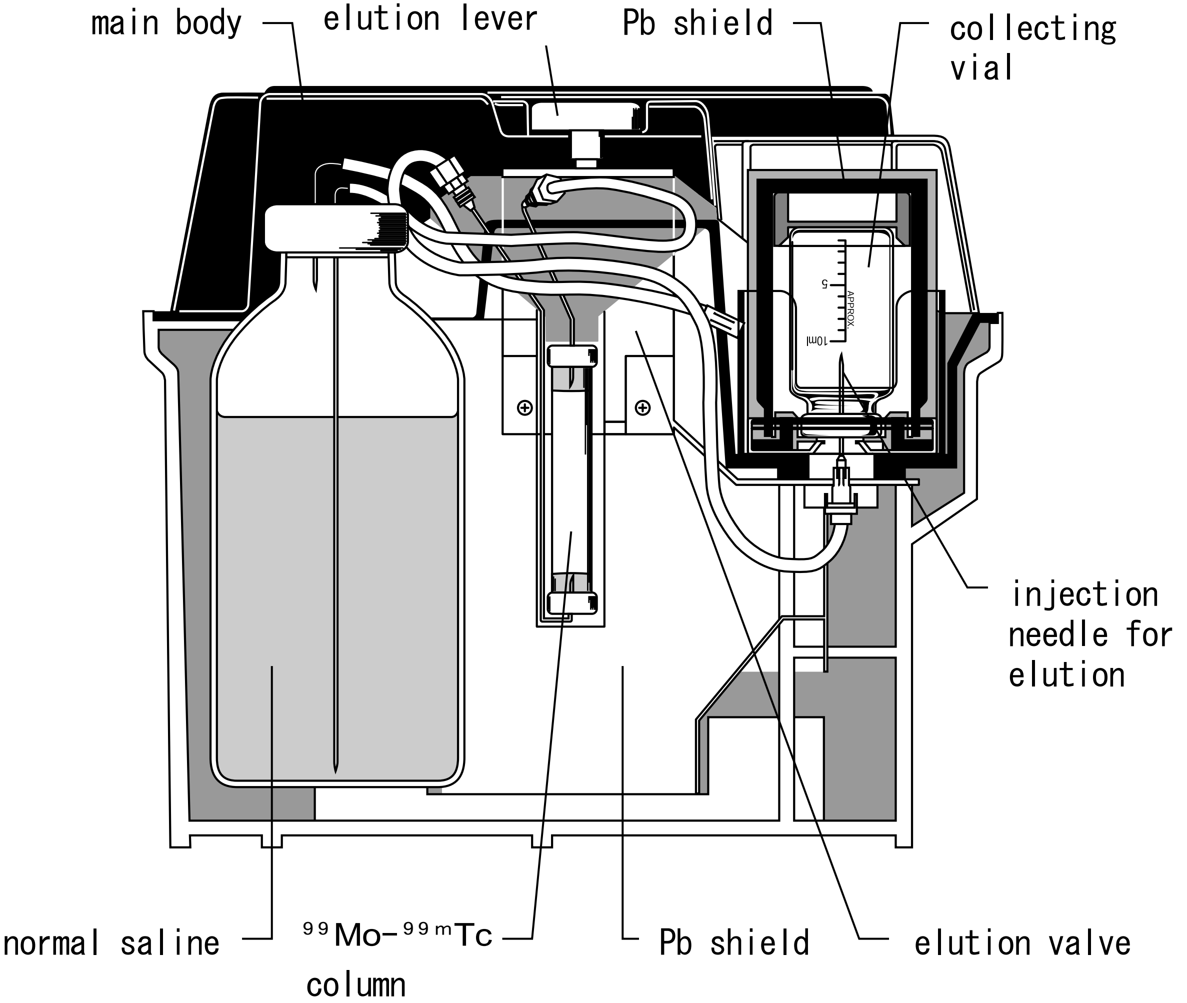
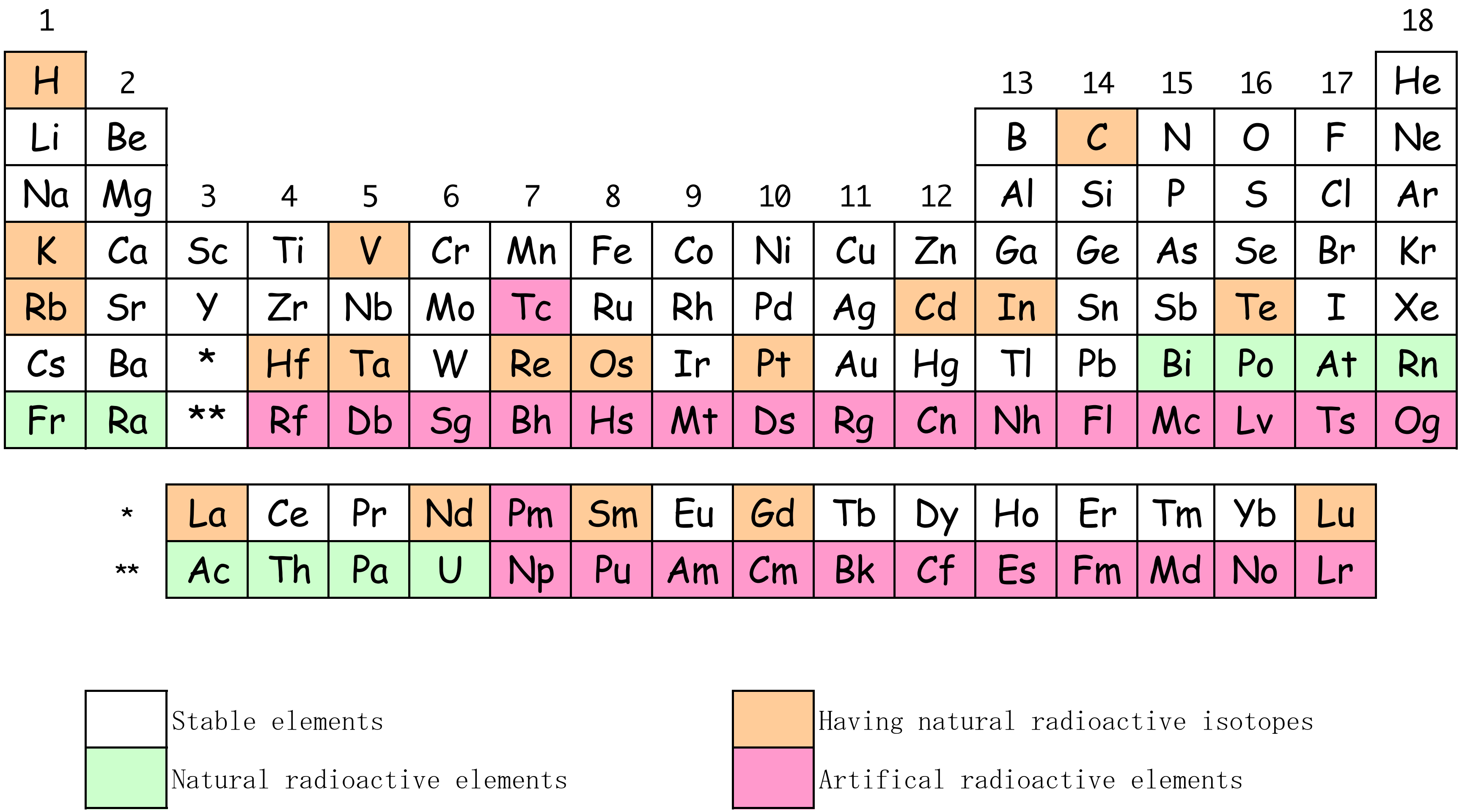


http://fri.fujifilm.co.jp/med/products/diagnosis/brain/utk/pack/pdf/fri_med_utk_attach.pdf

Natural radionuclides

- Primordial radionuclides
- Secondary radionuclides
- Induced radionuclides



1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
H																	He
Li	Be											B	C	N	O	F	Ne
Na	Mg											Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba	*	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra	**	Rf	Db	Sg	Bh	Hs	Mt	Ds	Rg	Cn	Nh	Fl	Mc	Lv	Ts	Og

*	La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
**	Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr

⬜ Stable elements

🟩 Natural radioactive elements

🟧 Having natural radioactive isotopes

🟪 Artifical radioactive elements

Primordial radionuclides

Nuclides that already existed when the solar system was formed and that still exist due to its long half life.

- *Parents of decay series*

^{238}U(4.5×10^{9} y), ^{235}U(7.0×10^{8} y), ^{232}Th(1.4×10^{10} y)

- *Independent*

^{40}K (1.3×10^{9} y)
^{50}V (1.4×10^{17} y)
^{87}Rb (4.8×10^{10} y)
^{115}In (4.4×10^{14} y)
^{123}Te (1.2×10^{13} y)
^{138}La (1.1×10^{11} y)
^{142}Ce ($>5\times10^{15}$ y)
^{144}Nd (2.3×10^{15} y)
^{147}Sm (1.1×10^{11} y)
^{148}Sm (7×10^{15} y)
^{152}Gd (1.1×10^{14} y)
^{176}Lu (3.8×10^{10} y)
^{174}Hf (2.0×10^{15} y)
^{187}Re (5×10^{10} y),
^{186}Os (2.0×10^{15} y)
^{190}Pt (6.5×10^{11} y)

Isotopic abundance > 10%

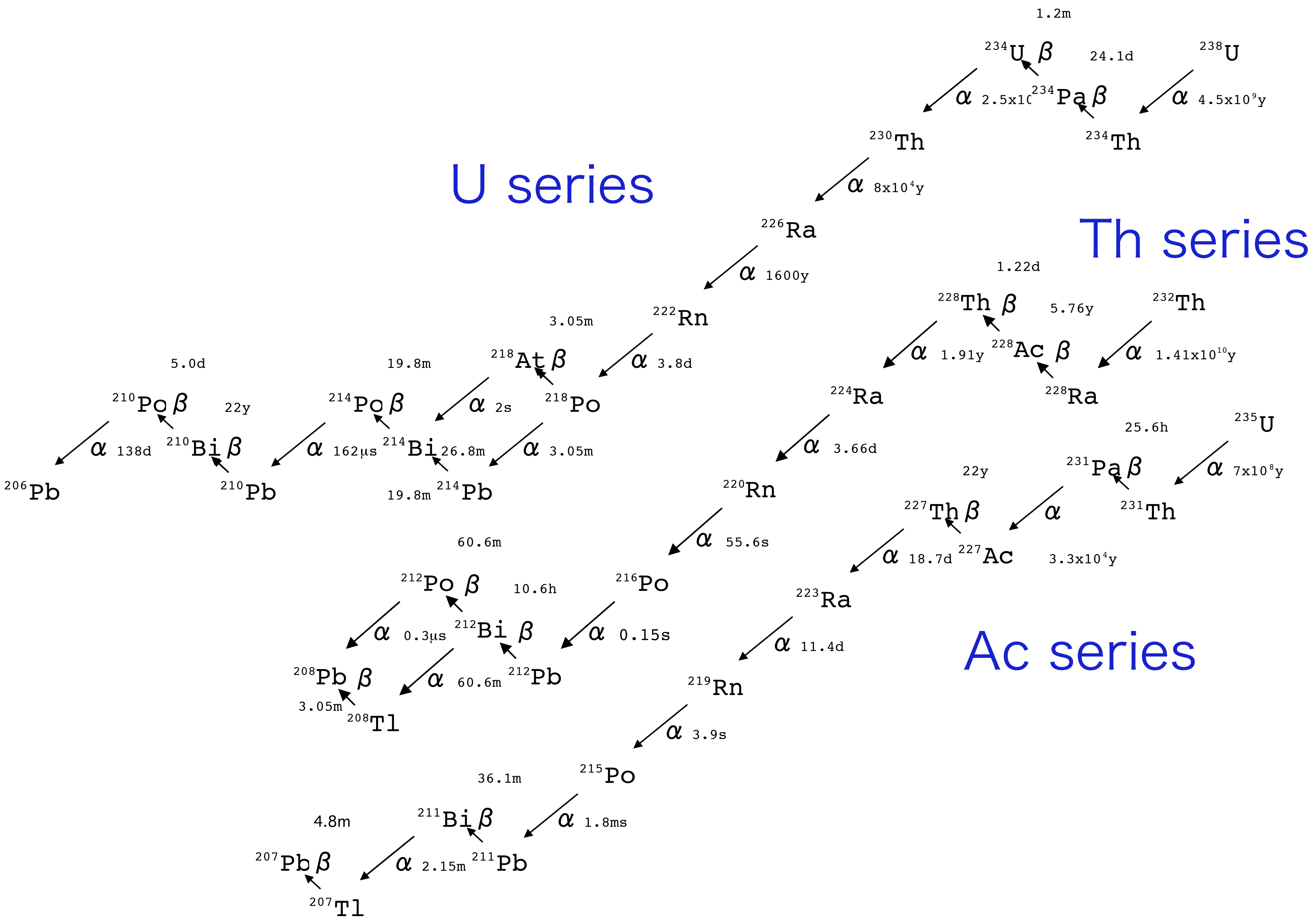
Secondary radionuclides

- Short-lived nuclides belonging to decay series originated in primordial radionuclides.
- Fission products of spontaneous fission

U series: ${}^{238}\mathrm{U} \rightarrow {}^{206}\mathrm{Pb}$, mass number = 4n + 2

Th series: ${}^{232}\mathrm{Th} \rightarrow {}^{208}\mathrm{Pb}$, mass number = 4n

Ac series: ${}^{235}\mathrm{U} \rightarrow {}^{207}\mathrm{Pb}$, mass number = 4n + 3


U series
Th series
Ac series
1.2m
²³⁴U β
24.1d
²³⁸U
α 2.5x10
²³⁴Pa β
α 4.5x10⁹y
²³⁰Th
²³⁴Th
α 8x10⁴y
²²⁶Ra
α 1600y
1.22d
²²⁸Th β
5.76y
²³²Th
3.05m
²²²Rn
α 3.8d
α 1.91y
²²⁸Ac β
α 1.41x10¹⁰y
5.0d
19.8m
²¹⁸At β
²²⁴Ra
²²⁸Ra
²¹⁰Po β
22y
²¹⁴Po β
α 2s
²¹⁸Po
25.6h
²³⁵U
α 138d
²¹⁰Bi β
α 162μs
²¹⁴Bi 26.8m
α 3.05m
α 3.66d
²⁰⁶Pb
²¹⁰Pb
19.8m
²¹⁴Pb
²²⁰Rn
22y
²³¹Pa β
α 7x10⁸y
²²⁷Th β
α
²³¹Th
60.6m
α 55.6s
α 18.7d
²²⁷Ac
3.3x10⁴y
²¹²Po β
10.6h
²¹⁶Po
²²³Ra
α 0.3μs
²¹²Bi β
α 0.15s
α 11.4d
²⁰⁸Pb β
α 60.6m
²¹²Pb
²¹⁹Rn
3.05m
²⁰⁸Tl
α 3.9s
36.1m
²¹⁵Po
4.8m
²¹¹Bi β
α 1.8ms
²⁰⁷Pb β
α 2.15m
²¹¹Pb
²⁰⁷Tl

Induced radionuclides

Nuclides that are always produced in the upper atmosphere mainly by nuclear reactions with cosmic rays in nature.

Nuclear spallation reactions of N and O

^{3}H (12.3 y), ^{7}Be (53.3 d), ^{10}Be (1.5×10^{6} y),
^{14}C (5.7×10^{3} y)

Nuclear spallation reactions of Ar

^{22}Na (2.6 y), ^{32}Si (172 y), ^{32}P (14.3 d),
^{35}S (87.5 d), ^{36}Cl (3.0×10^{5} y)

Induced radionuclides

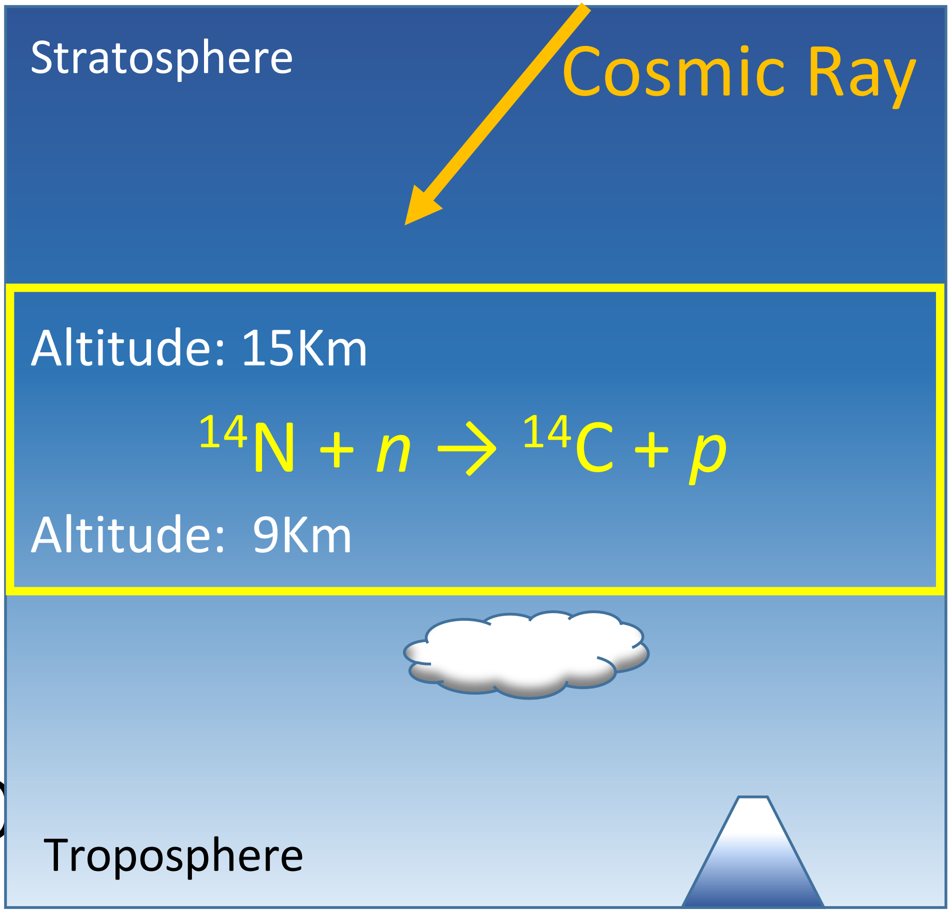
Nuclides that are always produced in the upper atmosphere mainly by nuclear reactions with cosmic rays in nature.

Nuclear spallation reactions

^{3}H (12.3 y), ^{7}Be (53.3 d),
^{14}C (5.7×10^{3} y)

Nuclear spallation reactions

^{22}Na (2.6 y), ^{32}Si (172 y),
^{35}S (87.5 d), ^{36}Cl (3.0×10

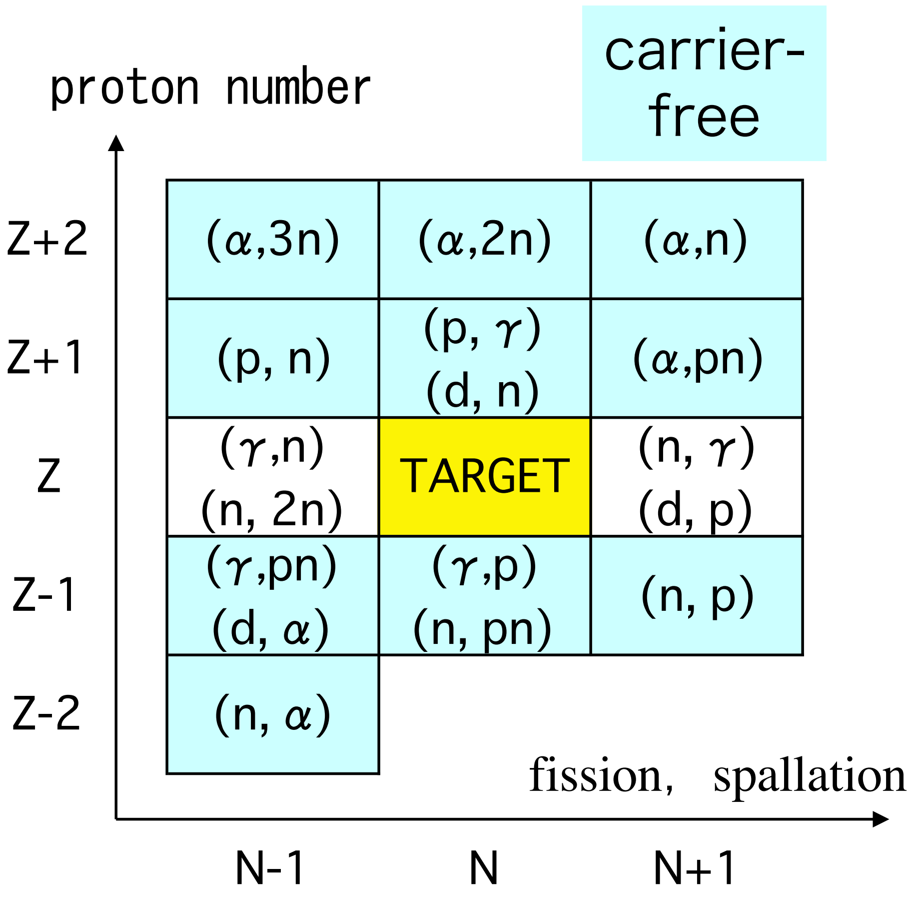


Artificial radionuclides

produced by nuclear reactions

- nuclear reactor (neutrons)
- accelerator (positive ions, electrons)

RI,
radioactive medicines



	N-1	N	N+1
Z+2	(α,3n)	(α,2n)	(α,n)
Z+1	(p, n)	(p, γ) (d, n)	(α,pn)
Z	(γ,n) (n, 2n)	TARGET	(n, γ) (d, p)
Z-1	(γ,pn) (d, α)	(γ,p) (n, pn)	(n, p)
Z-2	(n, α)		

$$^{18}\mathrm{O} + \mathrm{p} \rightarrow {}^{18}\mathrm{F} + \mathrm{n}$$

$$^{249}\mathrm{Cf} + {}^{48}\mathrm{Ca} \rightarrow {}^{294}118 + 3\mathrm{n}$$

Irradiation energy is important.

yields

secondary products

Radioactivity induced by nuclear reaction

$$N = n\phi\sigma t \qquad N / n = \phi\sigma t$$

$$A = n\phi\sigma\underbrace{(1 - e^{-\lambda t})}_{\text{saturation factor}}$$

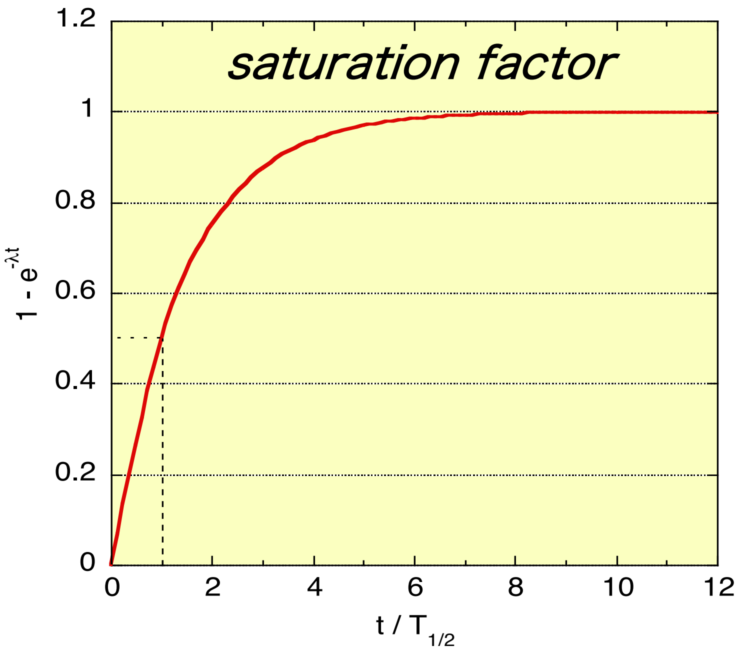
N : number of reactions
A : induced radioactivity
n : number of target nuclides
ϕ : fluence rate
σ : reaction cross section
λ : decay constant
t : irradiation time

(Ex.) $^{31}P(n,\gamma)^{32}P$, $T_{1/2}$ = 14 days

φ : 10^{13} $cm^{-2}s^{-1}$
σ : 0.17 b = 0.17×10^{-24} cm^2
λ : 0.049 d^{-1} = 5.7×10^{-7} s^{-1}
t : 14 d = 1.2×10^6 s

$$A = 1.6\times10^{10}\ \text{Bq/g}$$

$$N/n = 2.0 \times 10^{-6}$$



Nuclear fission

$$\underbrace{{}^{235}\mathrm{U} + \mathrm{n}}_{m_i} \rightarrow {}^{236}\mathrm{U} \rightarrow \underbrace{\overset{\beta^- \nearrow\, {}^{131}\mathrm{I}}{{}^{131}\mathrm{Sb}} + {}^{103}\mathrm{Nb} + 2\mathrm{n}}_{m_f} + Q$$

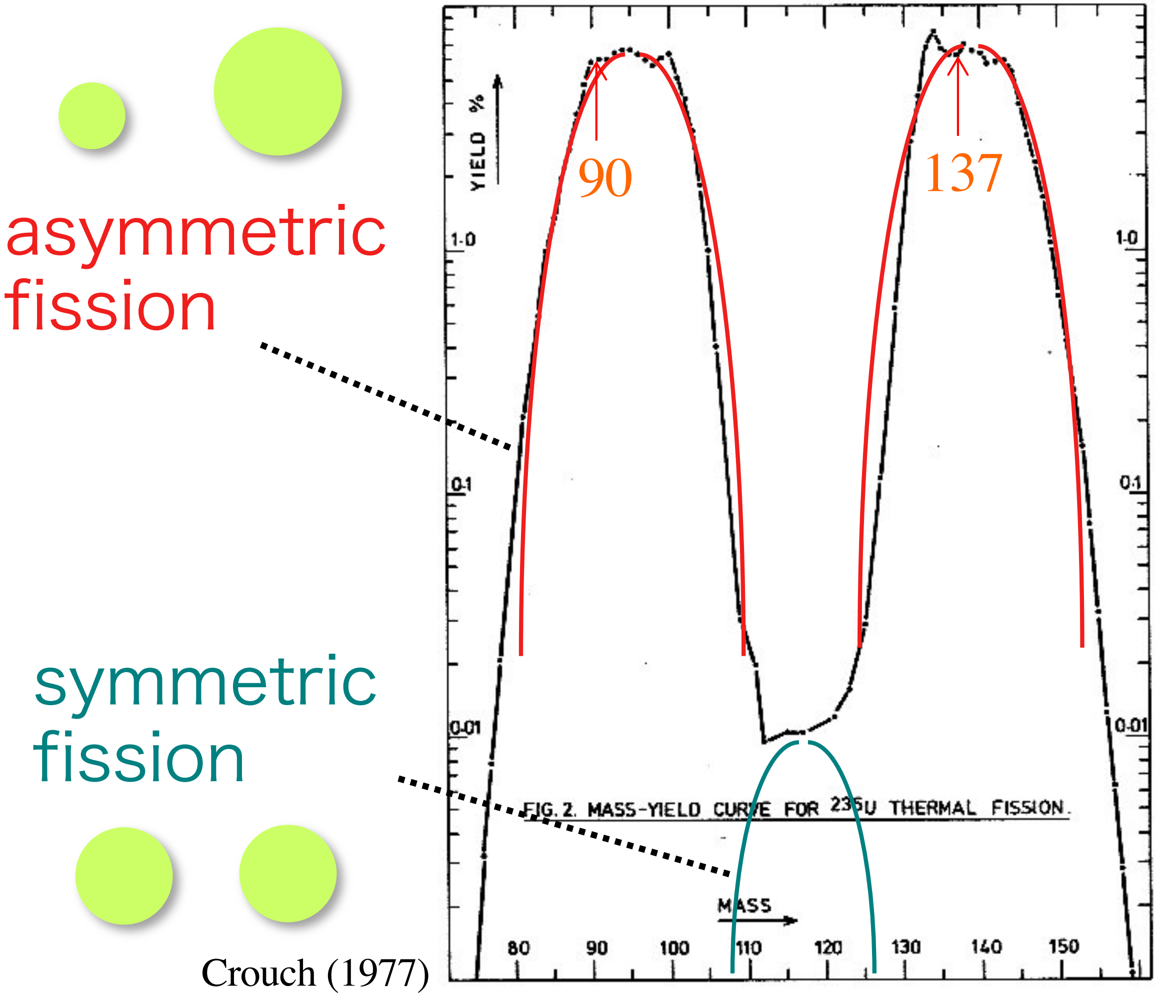


FIG. 2. MASS-YIELD CURVE FOR 235U THERMAL FISSION.

Crouch (1977)

$$m_i > m_f$$

$$Q = (m_i - m_f) \times c^2$$

$$\sim \quad 200\ \mathrm{MeV}$$

$$\boxed{1\ \mathrm{MeV} = 3.8\times10^{-17}\ \mathrm{kcal}}$$

1 g of ^{235}U = 2.5×10^{21} atoms

⇩

1.9×10^{7} kcal

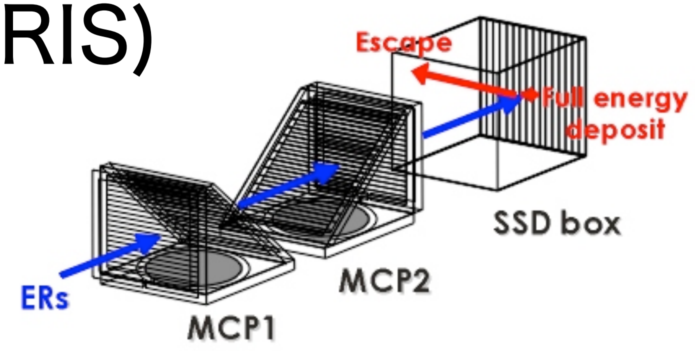
⇕

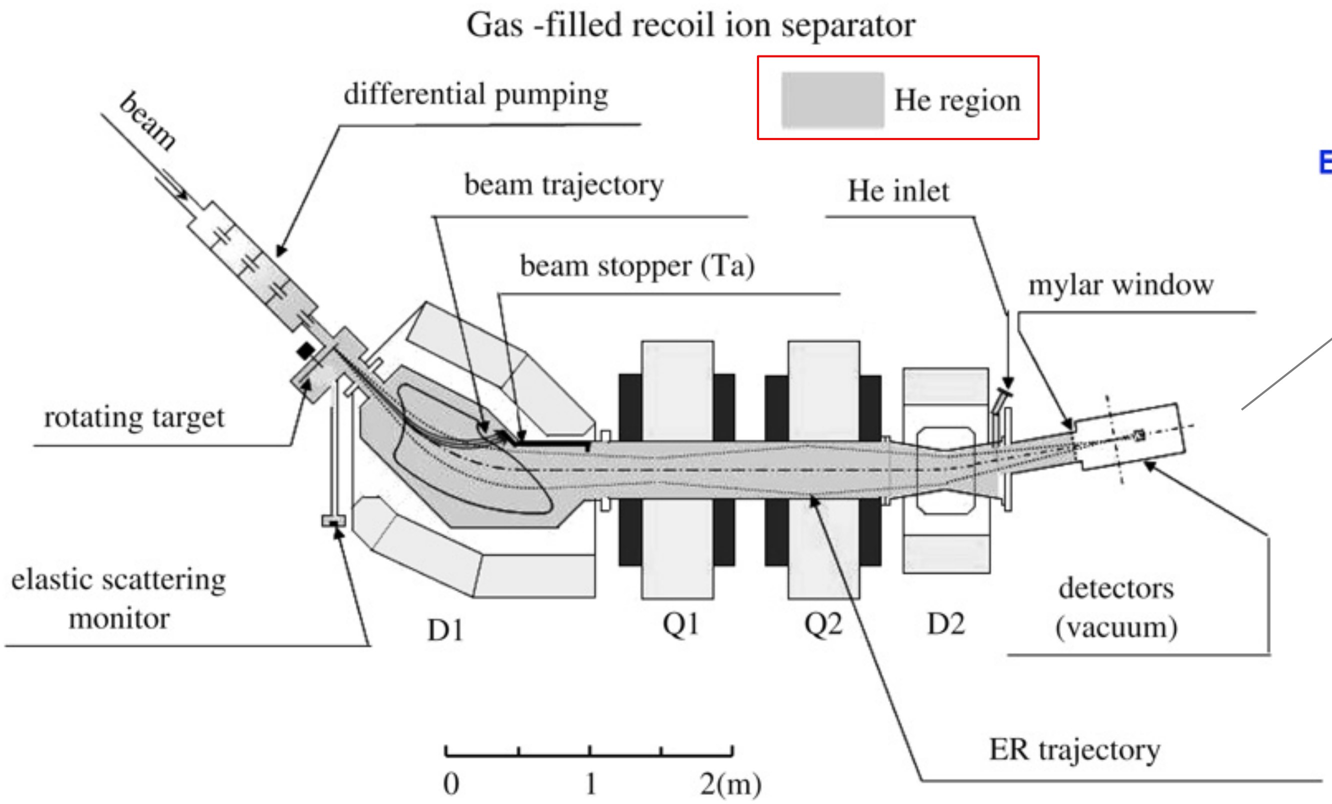
1 g of coal = 8.1 kcal

Element 113

$$^{209}\mathrm{Bi} + {}^{70}\mathrm{Zn} \rightarrow {}^{278}\mathrm{Nh} + \mathrm{n}$$

Gas-filled Recoil Ion Separator (GARIS)





Progress in Particle and Nuclear Physics 62 (2009) 325–336

Charge of ions become same by passing though gas.

various charge states

independent on initial charge state

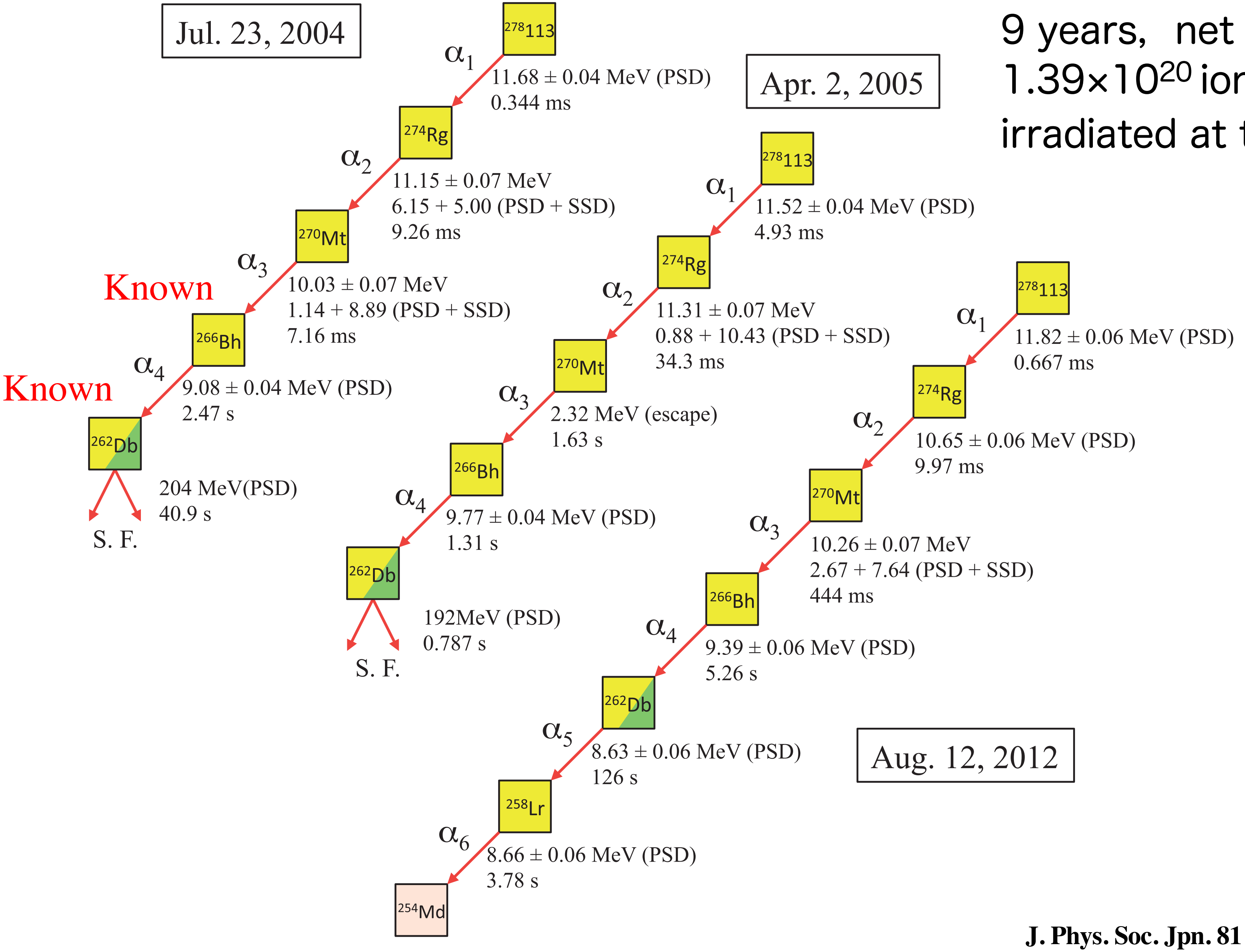
trajectory in magnetic field: $B\underline{\rho} = 0.0227\times\underline{A}\times(v/v_0)/\underline{q}$

radius mass number charge

Element 113

$^{209}Bi + {}^{70}Zn \rightarrow {}^{278}Nh + n$

9 years, net 574 days
1.39×10^{20} ions were
irradiated at the target.



Jul. 23, 2004

$^{278}113$
α_1 11.68 ± 0.04 MeV (PSD)
0.344 ms
^{274}Rg
α_2 11.15 ± 0.07 MeV
6.15 + 5.00 (PSD + SSD)
9.26 ms
^{270}Mt
α_3 10.03 ± 0.07 MeV
1.14 + 8.89 (PSD + SSD)
7.16 ms
Known
^{266}Bh
α_4 9.08 ± 0.04 MeV (PSD)
2.47 s
Known
^{262}Db
204 MeV(PSD)
40.9 s
S. F.

Apr. 2, 2005

$^{278}113$
α_1 11.52 ± 0.04 MeV (PSD)
4.93 ms
^{274}Rg
α_2 11.31 ± 0.07 MeV
0.88 + 10.43 (PSD + SSD)
34.3 ms
^{270}Mt
α_3 2.32 MeV (escape)
1.63 s
^{266}Bh
α_4 9.77 ± 0.04 MeV (PSD)
1.31 s
^{262}Db
192MeV (PSD)
0.787 s
S. F.

Aug. 12, 2012

$^{278}113$
α_1 11.82 ± 0.06 MeV (PSD)
0.667 ms
^{274}Rg
α_2 10.65 ± 0.06 MeV (PSD)
9.97 ms
^{270}Mt
α_3 10.26 ± 0.07 MeV
2.67 + 7.64 (PSD + SSD)
444 ms
^{266}Bh
α_4 9.39 ± 0.06 MeV (PSD)
5.26 s
^{262}Db
α_5 8.63 ± 0.06 MeV (PSD)
126 s
^{258}Lr
α_6 8.66 ± 0.06 MeV (PSD)
3.78 s
^{254}Md

J. Phys. Soc. Jpn. 81 (2012) 103201

Irradiation Effects of Radiation

(1) Radiation trauma

lattice defect (metal, semiconductor)

(2) Ionization, Excitation, Radical production

dissociation and formation of chemical bond
oxidation-reduction, cross-link, polymerization

(3) Killing of organisms, Asexualization

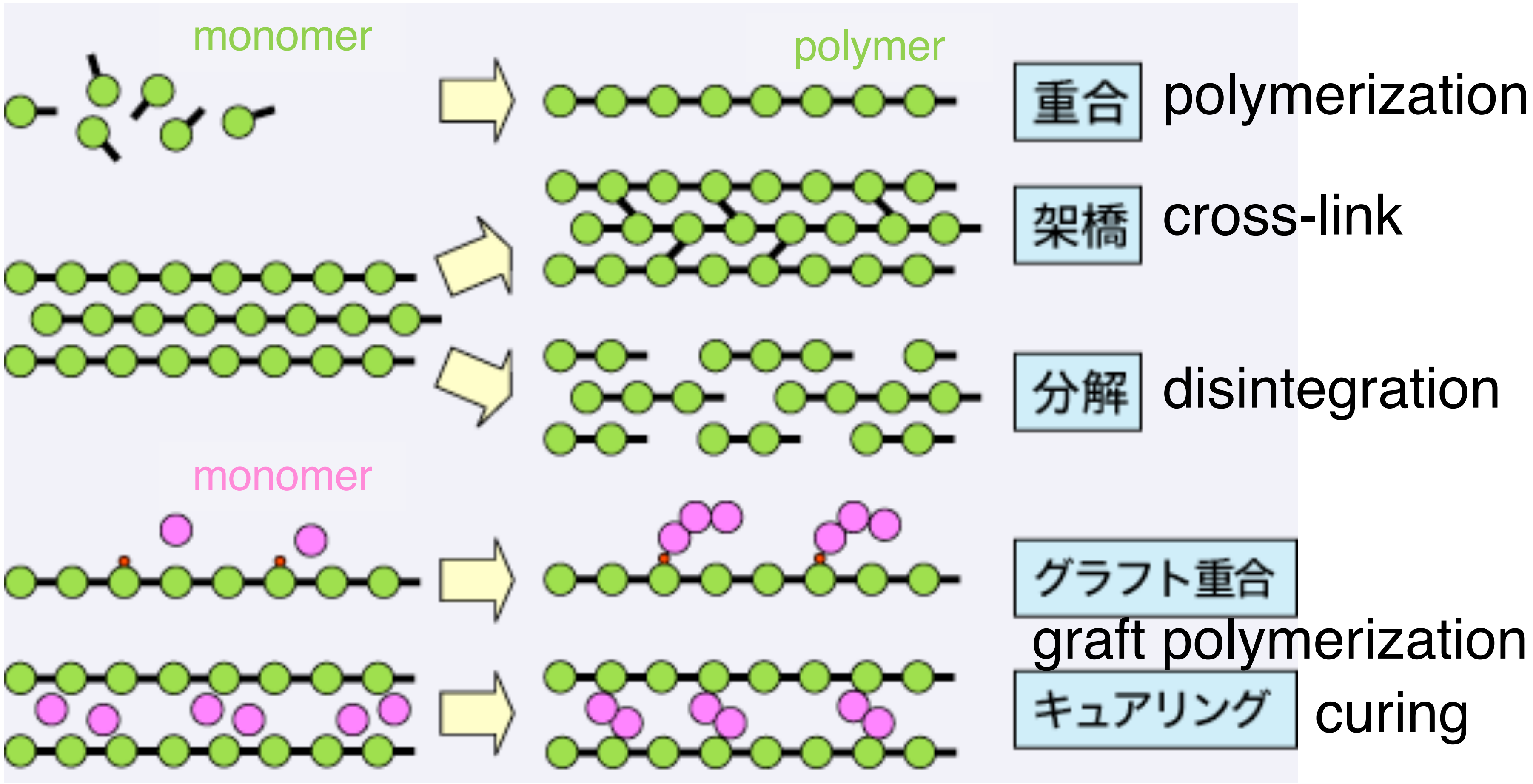
sterilization, pest control, food irradiation,
radiotherapy

(4) Mutation

cereal → (e.g.) Reimei [rice]
fruit → (e.g.) Gold 20 century [pear]
flower → (e.g.) Kirari [carnation]

https://www.pref.ibaraki.jp/nourinsuisan/seikoken/hinsyu/documents/h27kirari2.pdf

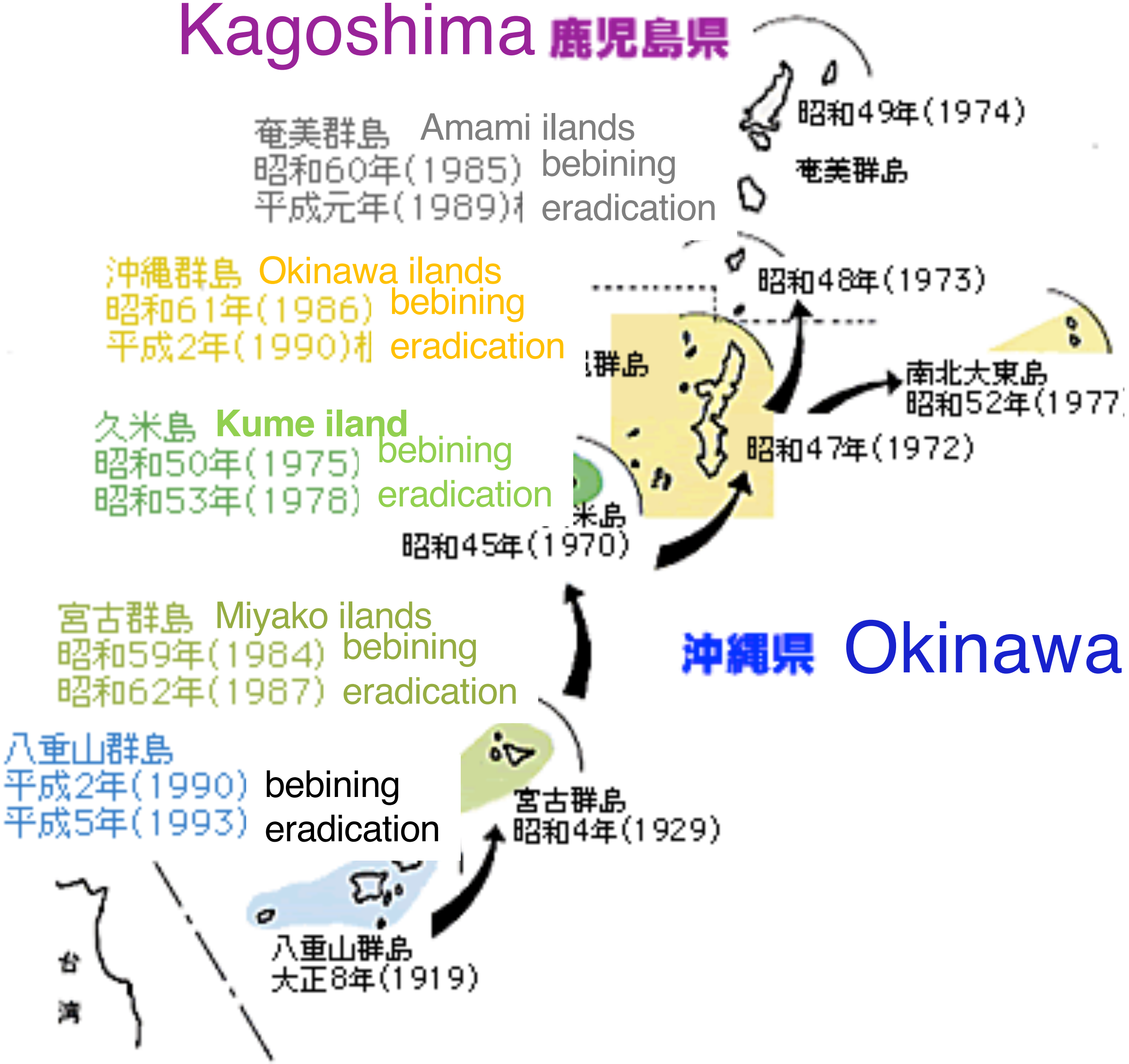
Reformulation and processing by radiaiton



- producton of fluorine resin(PTFE) particles [radiolysis]
- radial tire, heat resistance electric wire, foam plastic [cross-linking]
- painting cement tile, laminate steel sheet, paper liner of adhesive label [radiation curing]

http://www.radia-ind.co.jp/products/service01_05.htm#link

Prevention of melon fly



Kagoshima 鹿児島県

奄美群島 Amami ilands
昭和60年(1985) bebining
平成元年(1989) eradication

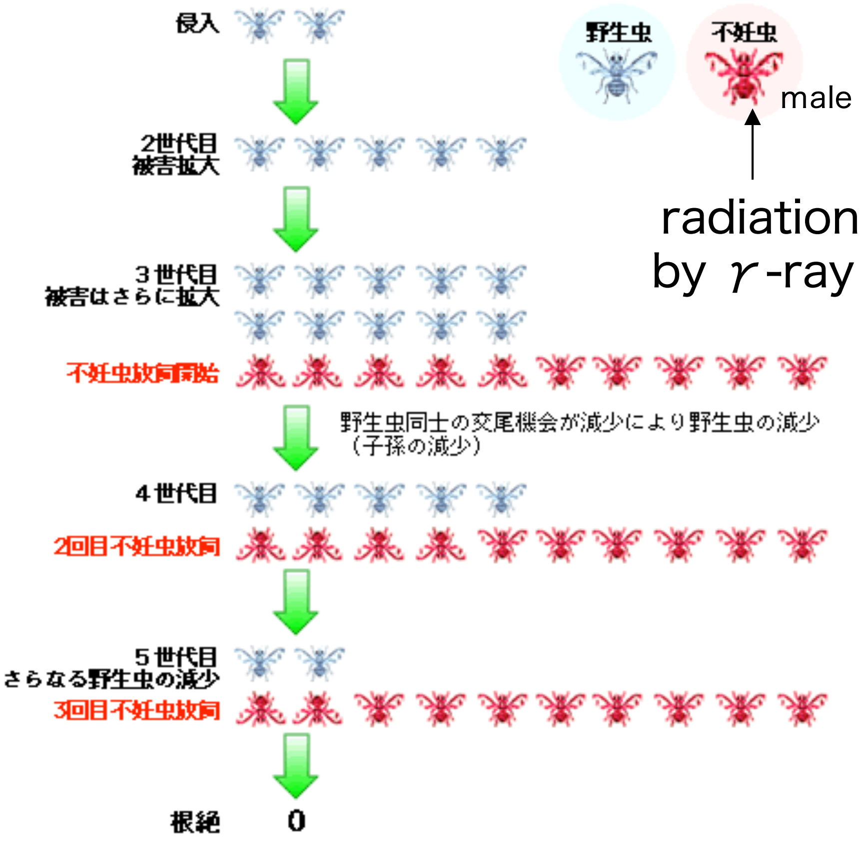
沖縄群島 Okinawa ilands
昭和61年(1986) bebining
平成2年(1990) eradication

久米島 **Kume iland**
昭和50年(1975) bebining
昭和53年(1978) eradication

宮古群島 Miyako ilands
昭和59年(1984) bebining
昭和62年(1987) eradication

八重山群島
平成2年(1990) bebining
平成5年(1993) eradication

沖縄県 Okinawa



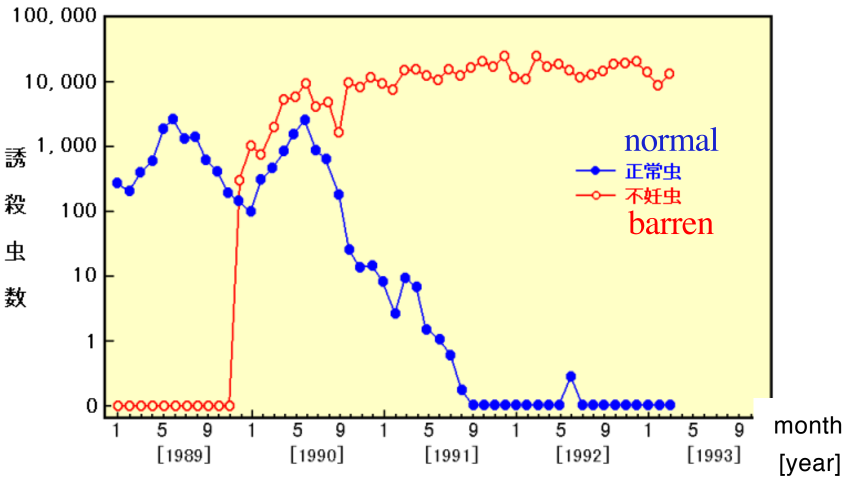


図3　八重山群島におけるウリミバエトラップ調査結果

[出典]沖縄県農林水産部特殊病害虫対策本部：平成4年 沖縄県特殊病害虫防除事業報告 第18号(1992年)p.24

https://www.pref.okinawa.jp/mibae/index.html
(沖縄県病害虫防除技術センター)