Nuclear Process & Radio-Analytical Chemistry

Class Notes – Part 1.3

Sources of Radioactive Nuclides

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Sources of Radioactive Nuclides

Nuclear Reactions

	Chemical	Nuclear
Change in energy	ΔH, heat of reaction	$Q = \Delta M c^2$
Minimum energy requirement	activation energy	threshold
Reaction rate	k	R

A chemical reaction written in the form

$$A + B \rightarrow C + D + \Delta H$$

A nuclear reaction written in the form

$$A + a \rightarrow B + b + Q$$

Nuclear reactions are usually written by using an abbreviated convention

$$A\,(a, b)\,B$$

Sources of Radioactive Nuclides

Nuclear Reactions

Irradiating Particle	Symbol of the (ionized) Projectile
Electromagnetic radiation (photons)	γ
Electrons	e
Neutrons	n
Hydrogen, ^{1}H (protons)	p
Deuterium, ^{2}H (deuterons)	d
Tritium, ^{3}H (tritons)	t
Helium-3, ^{3}He	^{3}He
Helium-4, ^{4}He (alpha particles)	α
Heavy ions	e.g., ^{6}Li, ^{12}C, etc.

Sources of Radioactive Nuclides

Nuclear Reactions

Nuclear reactions obey four conservation laws:

- Conservation of nucleons A
- Conservation of Charge Z
- Conservation of Mass-Energy E
- Conservation of Momentum p

The first two conservation law may be considered in our chemical reaction analogy as the balancing of the reaction

$$^{35}_{17}\mathrm{Cl} + {}^{1}_{0}\mathrm{n} \rightarrow {}^{32}_{15}\mathrm{P} + {}^{4}_{2}\mathrm{He} + Q$$

or, in abbreviated form,

$$^{35}\mathrm{Cl}(\mathrm{n},\alpha)^{32}\mathrm{P}$$

Sources of Radioactive Nuclides

Nuclear Reactions

The conservation of energy determines the reaction energy, which is equivalent to the difference in mass between the reactants and the products. Thus for the reaction

$$^{35}\mathrm{Cl}(\mathrm{n},\alpha)^{32}\mathrm{P} \tag{45}$$

$$\begin{aligned}\Delta M &= M(^{35}\mathrm{Cl}) + M(\mathrm{n}) - M(^{32}\mathrm{P}) - M(^{4}\mathrm{He}) \\ &= 34.96885 + 1.00867 - 31.97391 - 4.00260 \\ &= +0.00101 \text{ amu} \end{aligned} \tag{46}$$

$$Q = 931.4(\Delta M) = +0.94 \text{ MeV} \tag{47}$$

For this reaction $Q > 0$; that is, the mass of the products is lighter than the mass of the reactants. Such a reaction is exoergic. However, the reaction

$$^{32}\mathrm{S}(\mathrm{n},\mathrm{p})^{32}\mathrm{P} \tag{48}$$

has

$$\begin{aligned}\Delta M &= M(^{32}\mathrm{S}) + M(\mathrm{n}) - M(^{32}\mathrm{P}) - M(^{1}\mathrm{H}) \\ &= 31.97207 + 1.00867 - 31.97391 - 1.00783 \\ &= -0.00100 \text{ amu} \end{aligned} \tag{49}$$

$$Q = -0.93 \text{ MeV} \tag{50}$$

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Sources of Radioactive Nuclides

Types of Reaction

1. Neutron Reactions
   -*Neutron capture*
   -*Transmutation*
   -*Fission*

2. Charged Particle Reactions

3. Electron and Photon Reactions

Sources of Radioactive Nuclides

Types of Reaction

Neutron Reactions

-*Neutron capture:*

Most of common neutron activation reaction is neutron capture in which a low-energy neutron is absorbed by a nucleus with the prompt emission of a gamma ray

$$^{23}_{11}Na\ (n,\gamma)\ ^{24}_{11}Na$$

In the example above, the product isotope which is unstable with respect to beta-decay

$$^{24}_{11}Na \xrightarrow{\beta^-} {}^{24}_{12}Mg$$

Sources of Radioactive Nuclides

Types of Reaction

Neutron Reactions

-*Transmutation*

Examples:

$$^{27}_{13}Al\,(n,\,p)^{27}_{12}Mg \xrightarrow{\beta^-} {}^{27}_{13}Al$$

$$(n,\,p) \Rightarrow \textit{most probable}$$

$$(n,d) \qquad (n,t) \qquad (n,{}^3He) \qquad (n,\alpha) \Rightarrow \textit{with less probabilit y}$$

$$^{27}_{13}Al\,(n,\alpha)^{24}_{11}Na \xrightarrow{\beta^-} {}^{24}_{12}Mg$$

$$^{32}_{16}S\,(n,\alpha)^{29}_{14}Si\,(\textit{stable})$$

$$^{40}_{20}Ca\,(n,\alpha)^{37}_{18}Ar \xrightarrow{EC} {}^{37}_{17}Cl$$

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Sources of Radioactive Nuclides

Types of Reaction

Neutron Reactions

-*Fission*

- *The fission process involves the absorption of a neutron into the very heaviest elements (Z≳90)*
- *Results in the splitting of the nucleus into two large fragments*
- *Release of two to three neutrons*
- *This process lead to a chain reaction*

Sources of Radioactive Nuclides

Types of Reaction

Charged Particle Reactions

Charged particle reactions differ from neutron reactions primarily in the a charged particle approaching a target nucleus:

- *Proton reactions –*

$$^{45}_{21}Sc(p,n)^{45}_{22}Ti$$

- *Deuteron reaction -*

$$^{55}_{25}Mn(d,p)^{56}_{25}Mn$$

Sources of Radioactive Nuclides

Types of Reaction (electrons & photon)

- *For electrons and photons with energies below the neutron binding energies inelastic scattering may result in the creation of metastable isomers:*

$$^{115}In(e,n)^{114}In \qquad ^{103}Rh(\gamma,\gamma')^{103m}Rh$$

- *With energies above the neutron binding energies electrons and photons can induce photonuclear reactions with the emission of neutrons or other particles:*

$$^{103}Rh(\gamma,n)^{102}Rh \qquad ^{115}In(e,n)^{114}In$$

Sources of Radioactive Nuclides

Naturally Occurring

- Isotopes, stable and radioactive, of elements from He to Bi slowing formed by stellar (thermonuclear) burning
- Heavier Z nuclides quickly produced by exploding stars (supernovas): from Po to Md, all radioactive
- Light Z radionuclides made in earth's atmosphere by cosmic rays: ^{3}H, ^{7}Be, ^{10}Be, ^{14}C, ^{22}Na, ^{36}Cl, ^{39}Ar

Sources of Radioactive Nuclides

Naturally Occurring (4n)

$$^{232}_{90}Th \xrightarrow[1.405\times10^{10}\,y]{} {}^{228}_{88}Ra \xrightarrow[5.75\,y]{} {}^{228}_{89}Ac \xrightarrow[6.13h]{}$$

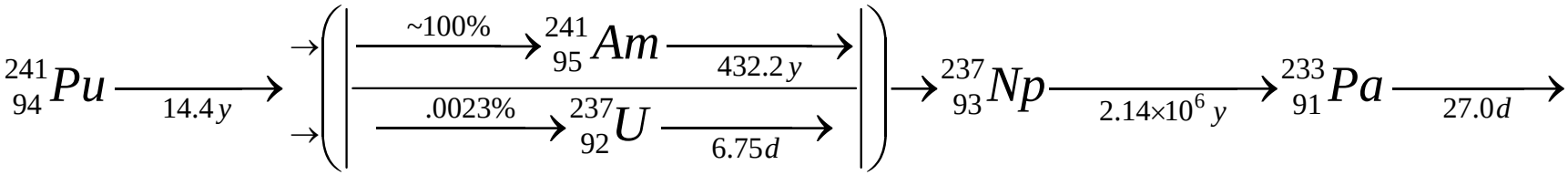
$$^{228}_{90}Th \xrightarrow[1.913y]{} {}^{224}_{88}Ra \xrightarrow[3.66d]{} {}^{220}_{86}Rn \xrightarrow[55.6s]{} {}^{216}_{84}Po \xrightarrow[.15s]{} {}^{212}_{82}Pb \xrightarrow[10.64h]{}$$

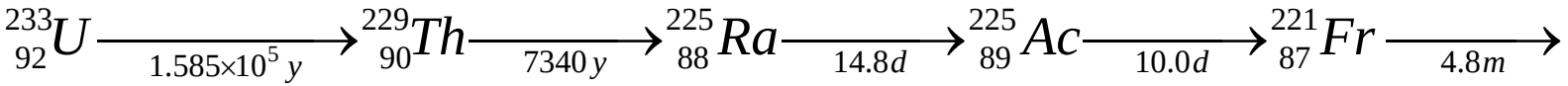
$$^{212}_{83}Bi \xrightarrow[60.55m]{} \rightarrow \left(\left| \begin{array}{l} \xrightarrow{64.07\%} {}^{212}_{84}Po \xrightarrow[305ns]{} \\ \xrightarrow{35.93\%} {}^{208}_{81}Tl \xrightarrow[3.07m]{} \end{array} \right| \right) \rightarrow$$

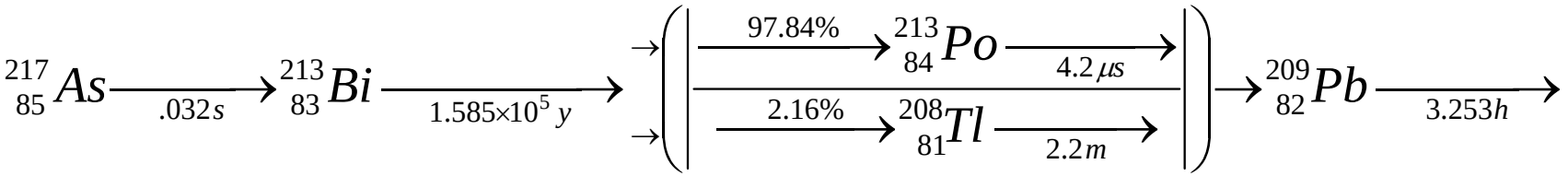
$$^{208}_{82}Pb(Stable)$$

Sources of Radioactive Nuclides

Naturally Occurring (4n + 1)



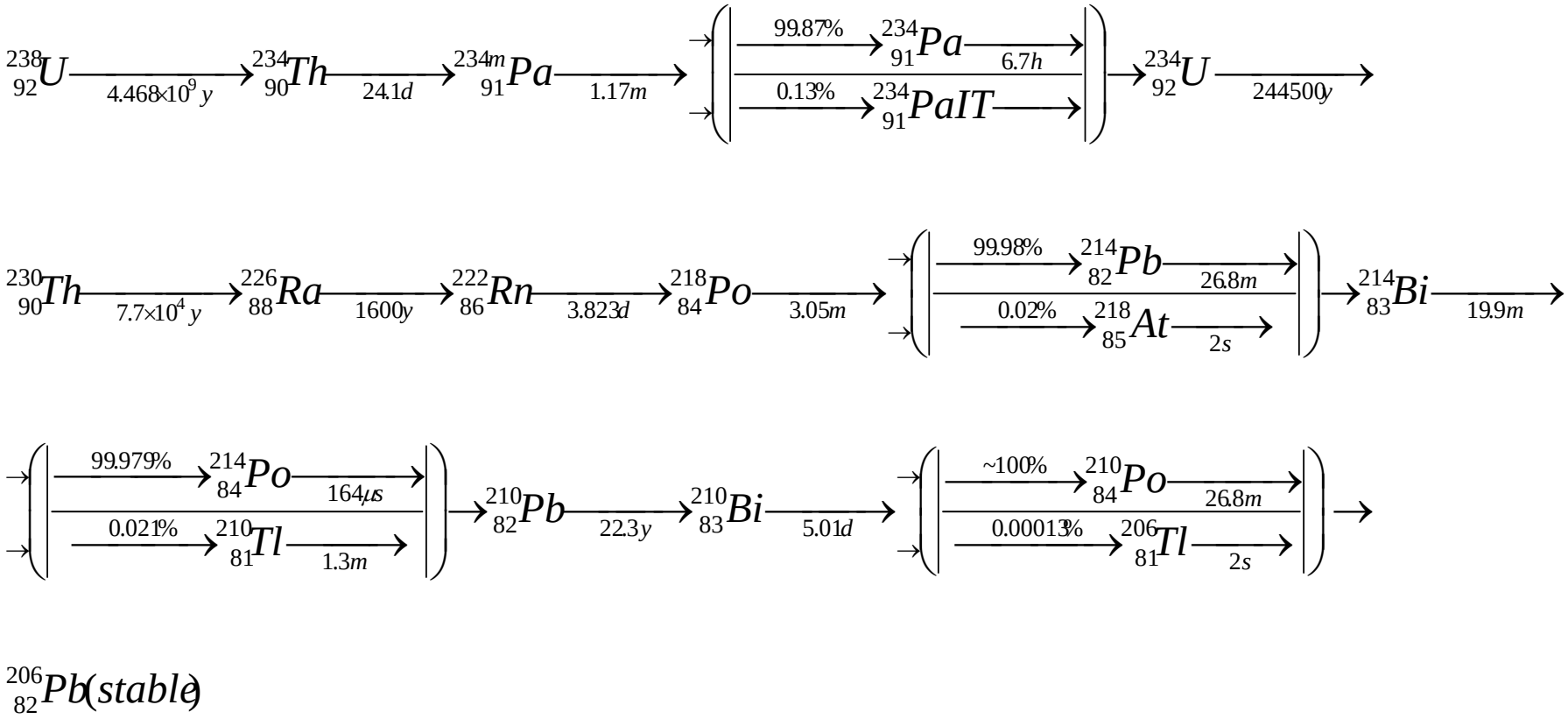




$^{209}_{83}Bi(Stable)$

Sources of Radioactive Nuclides

Naturally Occurring (4n + 2)



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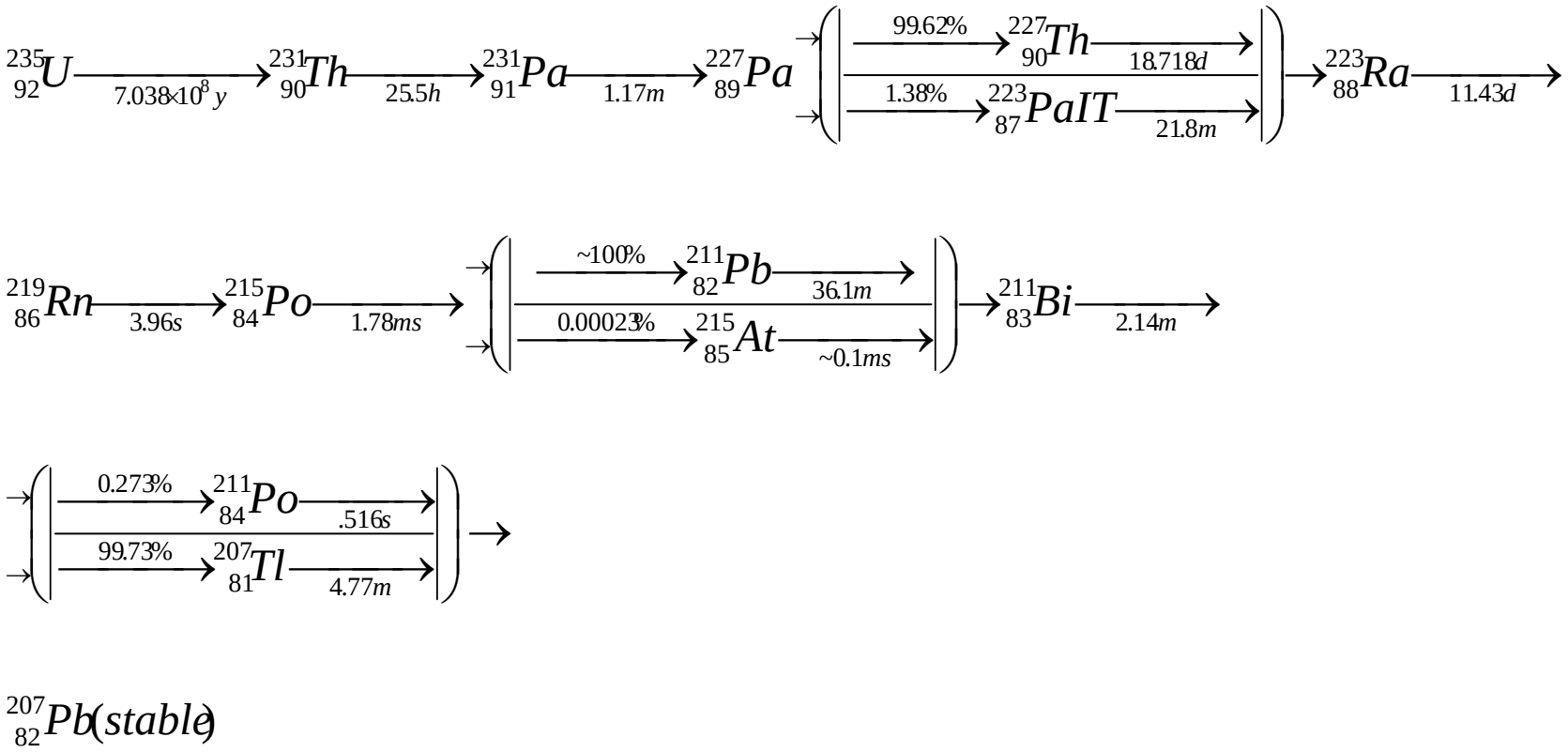
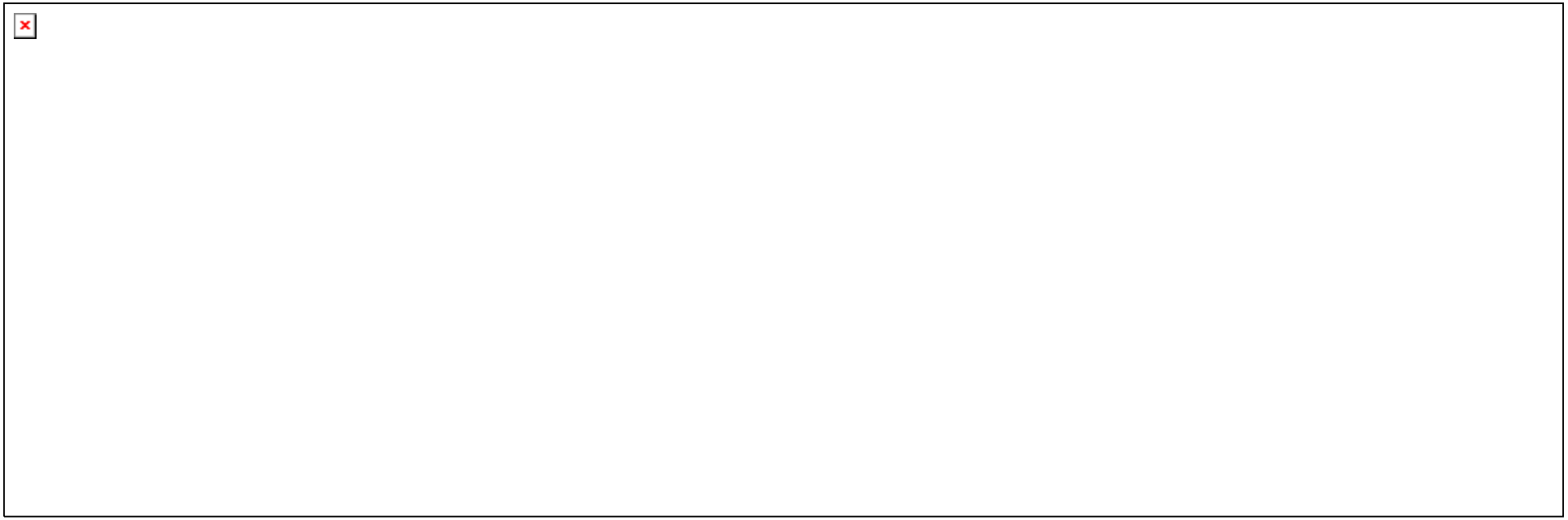
Sources of Radioactive Nuclides

Naturally Occurring (4n + 3)



Sources of Radioactive Nuclides



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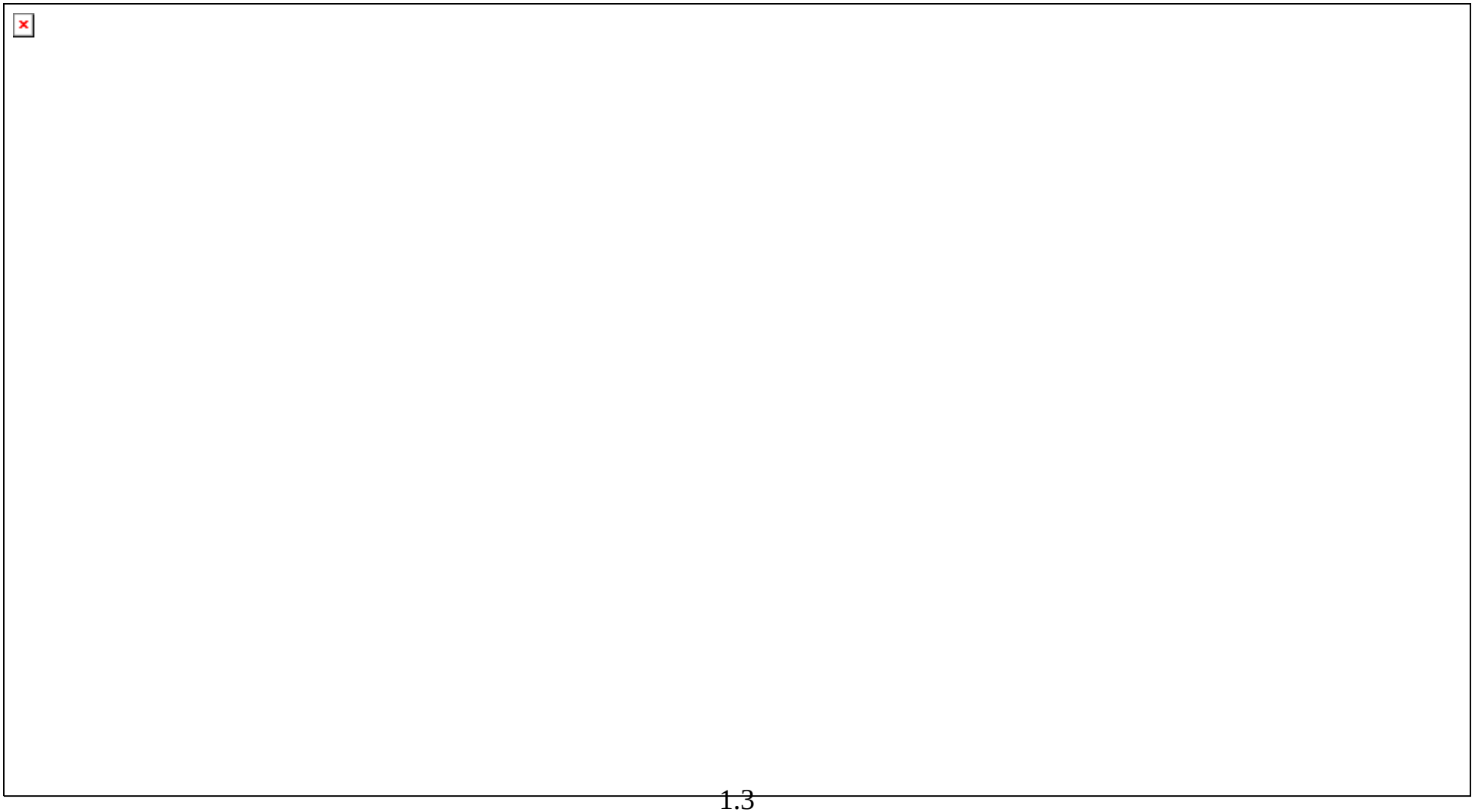
Sources of Radioactive Nuclides

Naturally Occurring (In addition to the four decay series)



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Sources of Radioactive Nuclides

Nuclear Reactors

- Most common reaction is neutron activation reaction
- Usually several radioisotopes produced unless target is monoisotopic
- Negatron emitters are usual products
- Length of irradiation and neutron flux affect which radionuclides formed

Sources of Radioactive Nuclides

Radioactive Waste

- Many sources, all manmade: U mill tailings, phosphate production, and coal power plan

- Types of radionuclides present varied:
    - Fission products: Sr-90, Tc-99, Eu-152
    - Activation products: H-3, C-14, Co-60
    - Concentrated primordial: Ra-226, Rn-222

Sources of Radioactive Nuclides

Particle Accelerators

- Types: linear and Van Der Graaff accelerators, cyclotron, synchrotron
- Bombarding particles usually small, positive ions: proton, $^{2}H^{+1}$, $^{3}H^{+1}$, $^{3}He^{+1}$, alpha
- Mostly neutron deficient isotopes produced: EC decay or positron

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Modes of Radioactive Decay