Radionuclides: Characteristics and Behaviour in the Environment

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A Very Brief Introduction to Radiation

Basic Facts You Need to Know

What is a Radionuclide?

- A **radionuclide** is an atom with an unstable nucleus
  - For each element, there is an optimum neutron/proton ratio for stability
  - Nuclides at the optimum ratio are usually stable; i.e. They are highly unlikely to spontaneously disintegrate
  - The further the neutron/proton ratio from the optimum, the less stable the nuclide and the more probable that a given atom will disintegrate within a specified time interval

[“Radionuclide” and “Radioisotope” are Synonyms]

What is a Radionuclide?

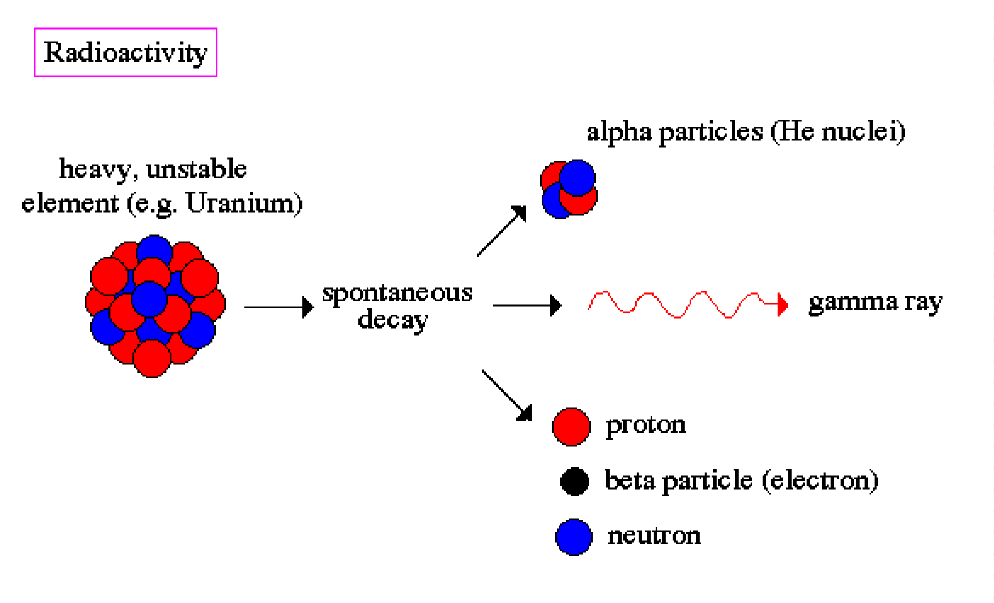
- The unstable nucleus attempts to reach stability by releasing energy

- The release of energy often results in the emission of **ionizing radiation**
  - The transfer of energy to a medium by radiation may be sufficient to overcome the binding energy of an electron – ejecting the electron from the atom – this is called *ionization*

Types of Radiation

Electromagnetic:
- X-rays
- Gamma rays

Particulate:
- **Alpha** – a proton plus a neutron (He nucleus); charge of +2
- **Beta** – an electron; may be + (positron) or – (beta)
  - Always accompanied by a neutrino (a low-energy, low-mass particle)
- Neutrons
- Protons



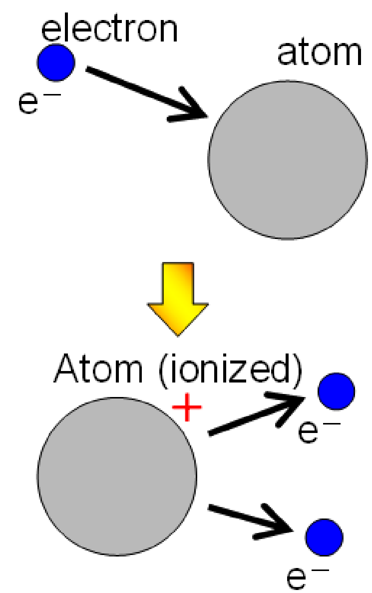
Two Categories

Example: Uranium

Electromagnetic Radiation

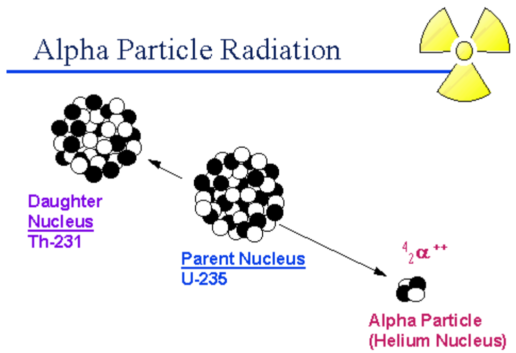
- X-rays and gamma rays are <u>indirectly</u> ionizing:

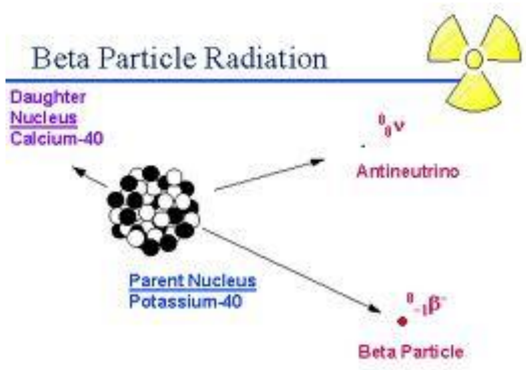
  - Energy is released when the rays interact with a medium (tissue, soil) – producing a fast-moving particle such as an electron
  - It is the *electron* that then secondarily may react with a target molecule causing ionization
  - Because electromagnetic radiation has no mass or charge, it can pass through the human body, but will be absorbed by denser materials such as concrete or lead



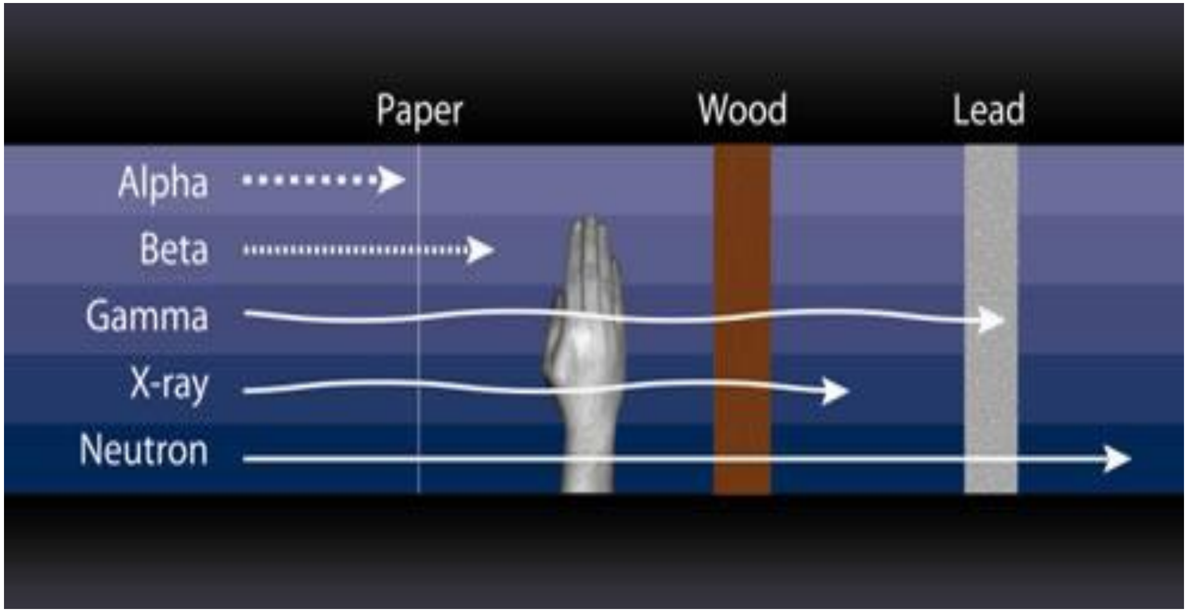
Particulate Radiation

- Alpha and beta particles and neutrons are directly ionizing – they strike the tissue or medium and directly react with target molecules such as oxygen and water
- Alpha particles are barely able to penetrate skin and can be stopped completely by a sheet of paper.
- Beta particles are more penetrating, but can still be stopped by a small amount of shielding, such as a sheet of plastic.
- Neutron radiation is absorbed by materials with lots of hydrogen atoms, like paraffin wax and plastics





Penetration of Different Types of Radiation



From
http://nuclearsafety.gc.ca/eng/readingroom/radiation/types_sources_of_radiation.cfm

Effects of The Different Types of Radiation

- Electromagnetic radiation penetrates farther into media (soil/water/tissue)
- Particulate radiation does not penetrate as far because it loses much more energy per unit distance
- Therefore, particulate radiation causes more ionization per unit distance than electromagnetic radiation

Linear Energy Transfer of Various Types of Radiation

Type of Radiation	LET (keV/μ)	Relative Biological Effectiveness
Gamma and x-rays	0.3-10	1.0
Beta Radiation	0.5-15	1-2
Neutrons	20-50	2-5
Alpha Radiation	80-250	5-10

Relative Biological Effectiveness = the relative amount of energy transfer to tissue. Biologic effectiveness is usually due to localized deposition of energy affecting critical structures such as DNA.

Potential to Cause Effects

Which types of Radiation would have the most potential to cause biological effects, assuming the same starting amount of energy release?

Types of Radionuclides

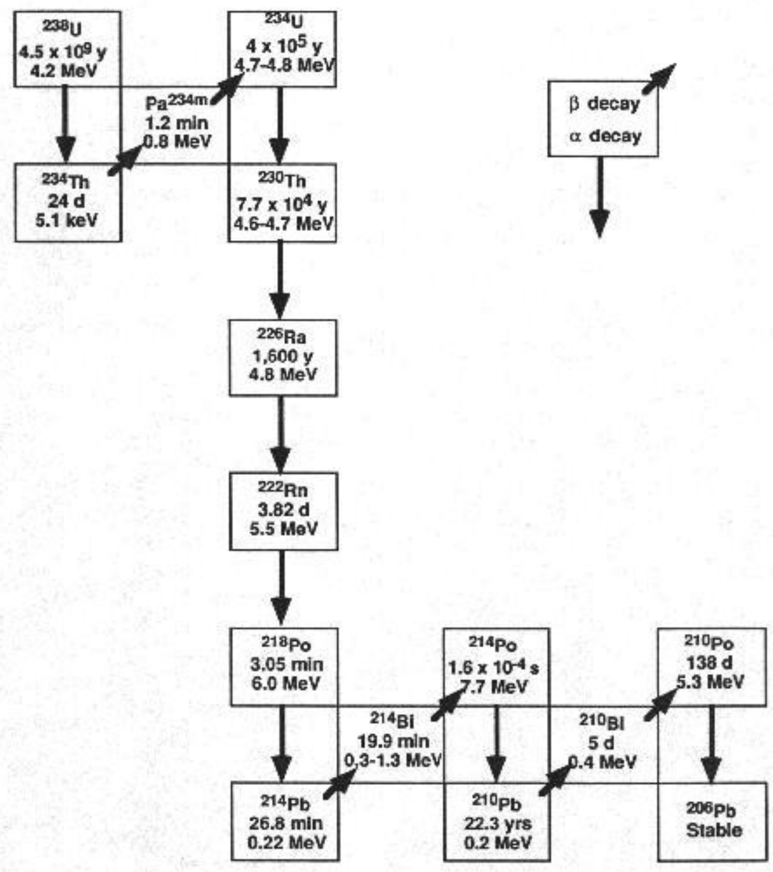
- Radioactivity and Half-Life

Measurement of Radioactivity

Origin of Radionuclides

Radioactivity

- Radioactivity is the result of a parent radionuclide spontaneously disintegrating, releasing one or more radiations (gamma, beta etc) and forming a daughter nuclide
- The number of nuclear disintegrations per unit time is proportional to the amount (mass or number of atoms) of radioactive material in a sample



Radioactivity results from decay to a stable form

U-238 Decay Chain

Half-Life

- The half-life is the amount of time it takes for half of the number of radioactive atoms to disintegrate (also called decay)

  - E.g.
    - Uranium half-life = 4.5 billion years
    - Radon half-life = 3.8 days

- Half-lives vary from seconds to billions of years

Half-Life and Specific Activity

Specific activity = the number of disintegrations per unit time

- The shorter the half-life, the higher the specific activity

Which would be more “radioactive” – uranium or radon?

Measurement of Radioactivity

- International Unit of Radioactivity is the Becquerel (Bq). One Bq= 1 disintegration/sec
- Radionuclide content usually expressed per unit mass or volume; e.g. Bq/g; Bq/L
- Natural background radionuclide concentrations are usually in mBq; e.g. 20 mBq/L Radium-226 in water

Radiation Dose

- As radiation passes through matter, some of its energy is "absorbed" by the matter. This is referred to as the **absorbed dose**, and the measurement of this dose is given in grays (Gy)
- Different types of radiation (alpha, beta, etc.) have different effects on tissue because of different biological effectiveness. To account for these differences, the absorbed dose is multiplied by a *radiation weighting factor*. This factor is dependent upon the type and amount of radiation involved. The result is referred to as the **equivalent dose**, and it is expressed in sieverts (Sv).
- 1 Sv = 1 joule/kg

- **Dose limit for the general public = 1 mSv/year (not including background and medical exposure)**

Origin of Radionuclides

Naturally occurring radionuclides fall into three categories:

1. primordial radionuclides
2. secondary radionuclides
3. cosmogenic radionuclides

Primordial Radionuclides

- Primordial radionuclides originate mainly from the interiors of stars
- Singly-occurring or parents of decay chains

- <u>E.g. singly-occurring</u>
  - Potassium-40: half-life = 1.26 billion years
  - Rubidium-87: half-life = 48 billion years
- <u>E.g. Parents of decay chains</u>
  - Uranium-238: half-life = 4.5 billion years
  - Thorium-232: half-life = 14 billion years

- Still present because their half-lives are so long that they have not yet completely decayed.
- Weathering releases them to soil and water, with further distribution via dust, sedimentation, and food chain uptake

Secondary Radionuclides

- Secondary radionuclides are the daughters of the parent primordial radionuclides
- They have shorter half-lives than primordial radionuclides
- E.g.
  - Radium-226: half-life = 1622 years
  - Lead-210: half-life = 138 days
- Weathering releases them to soil and water, with further distribution via dust, diffusion (if a gas), sedimentation and food chain uptake

Cosmogenic Radionuclides

- Continually formed in the atmosphere by cosmic rays
- E.g.
  - Carbon-14: half-life = 5730 yrs
  - Phosphorus-32: half-life = 14 days
  - Tritium (H^3): half-life = 12 years
- Atmospheric distribution and deposition to soil and water
- Further distribution (if half-life is sufficient) via dust, diffusion, sedimentation, and food chain uptake

Artificial Radionuclides

- Produced by nuclear reactors, nuclear and thermonuclear explosions, particle accelerators, radionuclide generators

Nuclear Reactors

- High flux of neutrons produced in the reactor <u>activates</u> elements placed within the reactor.
- Some of the same radionuclides as produced by cosmic radiation; e.g. C-14, tritium, P-32
- Others include:
  - Co-60: half-life = 5.2 years
  - Zn-65: half-life = 245 days
  - Plutonium-239: half-life = 24, 360 years
- Release to the environment highly controlled – primarily via air emissions (tritium), spills, or storage of spent fuels

Nuclear and Thermonuclear Explosions

- Fallout from past atmospheric nuclear explosions is a significant source of artificial radioactivity in the biosphere
- 1963 – Nuclear Test Ban Treaty between US and USSR
- Other countries (e.g. China and France) have continued atmospheric testing
- Fission products
  - E.g. Sr-90: half-life = 28 years
  - I-131: half-life = 8 days
  - Cs-137: hlf-life = 30 years
- Neutron-activation products
  - E.g. Tritium, C-14,
  - K-42: half-life = 12 hrs;
  - Ca-45: half-life = 152 days

Particle Accelerators and Radionuclide Generators

- Particle accelerators such as cyclotrons accelerate particles to bombard a target to produce radionuclides. Cyclotrons accelerate protons at a target to produce positron emitting radioisotopes e.g. fluorine-18.

- Radionuclide generators contain a parent isotope that decays to produce a radioisotope. The parent is usually produced in a nuclear reactor.

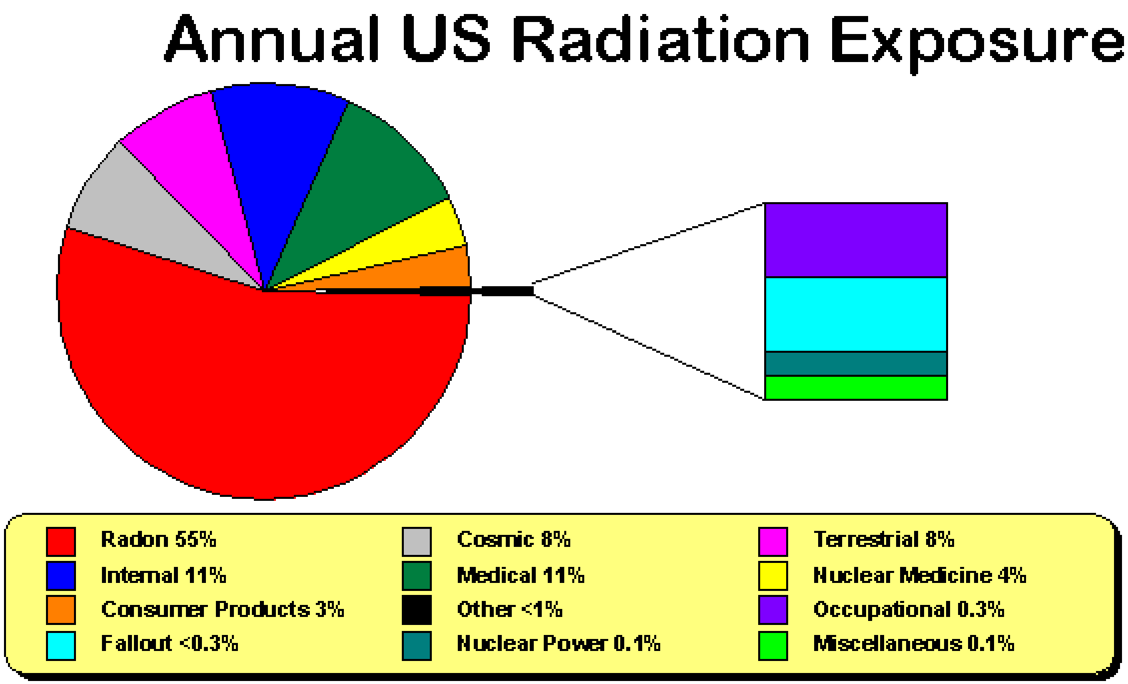
- E.g. technetium-99m generator used in nuclear medicine. The parent produced in the reactor is molybdenum-99.

- Release to environment highly controlled; accidental releases and air emissions are primary sources

Summary Table

Stability Class	Number of Nuclides	Notes
Theoretically stable to all but proton decay	90	Includes first 40 elements. Proton decay yet to be observed.
Energetically unstable to one or more known decay modes, but no decay yet seen. All considered "stable" until decay detected.	165	Classically stable nuclides
Primordial radionuclides	33	Total primordial elements include bismuth, uranium, thorium, plutonium, plus all stable nuclides.
Daughter and Cosmogenic radionuclides	~51	Carbon-14 (and other isotopes generated by cosmic rays); daughters of radioactive primordials, such as radium, etc.
Artificial: half-life>1 hr	556	Includes most useful radiotracers

Typical Radiation Exposure



http://www.google.ca/imgres?imgurl=http://www.radiationcontrol.utah.gov/images/bkgd_rad.gif&imgrefurl

The Key Basic Facts About Radionuclide Decay

- Radionuclides have unstable nuclei
- Radionuclides disintegrate to “seek” a more stable state
- Disintegration produces electromagnetic (x-ray and gamma) and/or particulate (alpha, beta, neutron) radiation
- The number of disintegrations/sec determines the half-life
- The shorter the half-life, the more radioactivity
- Particulate radiation has a higher potential to damage biological tissue

The Key Basic Facts About Types of Radionuclides

- Natural radionuclides are primordial, secondary or cosmogenic

- Artificial radionuclides are produced by nuclear reactors, nuclear explosions, particle accelerators or radionuclide generators

- Both natural and artificial radionuclides are widely distributed in the biosphere

Behaviour of Radionuclides in the Environment

- Chemical Properties
  Fate and Transport

Groups According to Chemical Properties

- Nonmetals (H,C,P,I)
- Light Metals (K, Rb, Cs, Ca, Sr, Ba, Ra)
- Noble gases (A, Kr, Xe Rn)
- Heavy metals (Cr, Mn, Fe, Co, Zn, Zr, Ru, Pb, Po)
- Rare earths (Y, La, Ce, Pr, Pm)
- Actinides (Th, U, Pu)

Assessing the potential for uptake and effects from radionuclides

- If you were told that cesium-137, radon and uranium were all present at a site you were investigating, which radionuclide would you be most concerned about:
  - With respect to how radioactive each radionuclide was
  - With respect to how likely uptake into the food chain was
  - With respect to the most likely exposure route

Key Basic Facts About Radionuclide Behaviour in the Environment

1. Chemical behaviour will be similar to stable elements in the same chemical group

2. The same governing variables affect radionuclide uptake:
   - pH, redox, soil or sediment particle size, organic carbon, sulphides in sediments, iron/manganese oxides, cation exchange capacity, presence of complexing agents such as humic acids

3. If the radionuclide is a chemical analogue of an essential nutrient, uptake of the radionuclide will increase if the nutrient is scarce

If you ever have to deal with radionuclides in the environment...

- Find out the type of radionuclide
- Assess the radiation hazard according to the half-life and specific activity (shorter the half-life the more radioactive) and prepare a health and safety plan accordingly (with help from a radiation expert)
- Assess the potential for transport by measuring controlling variables such as pH, Eh etc.
- Assess the potential for uptake into food chains by understanding how mobile the radionuclide is at your site (see above)

Radionuclide	Sources	Nutrient Analogues	Principal Biosphere Reservoirs	Exposure Modes	Degree of Food Chain Transport	Successive Trophic Level Concentration
Tritium	Cosmic Fission Activation	H	Water	Ingestion Absorption Inhalation	High	Approaches Unity
Potassium-40	Primordial	K	Lithosphere	Ingestion Absorption External gamma	High	Approaches Unity
Cesium-137	Fission	K	Soil, Sediments	Ingestion Absorption External gamma	High	Approaches 3.0
Radium-226	U-238 decay series	Ca	Lithosphere	Ingestion Absorption External gamma	Moderate	<1.0
Radon-222	U-238 decay series	None	Lithosphere	Inhalation of daughters	Negligible	<1.0
Lead-210	U-238 decay series	None	Soil, Sediments	Ingestion Inhalation Adsorption	High	<1.0-10
Rare earths	Fission	None	Soil, sediments, biota	Ingestion Inhalation Adsorption External gamma	Low except moderate for Cerium-144	<1.0
Uranium-238	Primordial	S, Se (?)	Lithosphere	Ingestion Inhalation External gamma	Low-Moderate	<1.0

From:Whicker and Schultz 1982 Radioecology: Nuclear Energy and the Environment

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Questions and Discussion

Nonmetals: Tritium

- Half-life 12 yrs: via beta particles
- Lightest and one of the most widely distributed radionuclides
- Vast majority of tritium found as tritiated water
- Generally follows the hydrologic cycle
- Initial behaviour determined by source – if released as gas or vapour substantial dispersion occurs with rapidity of deposition dependent on climatic factors
- Unique because does not adsorb to sediments or biotic surfaces as with most other radionuclides
- Enters plants via roots, leaves and stems with high efficiency
- Enters animals through ingestion, inhalation and direct absorption through the skin
- Seldom if ever concentrated in biological tissues to levels greater than in air or water

The natural concentration of tritiated water in air is most often below analytical limits of detection with occasional values found of up to about 1 Becquerel per cubic metre (Bq/m3)

Nonmentals: Phosphorus-32

- Half-Life = 14 days via beta particles
- Frequently introduced into the environment
- Often used as a tracer for P
- Mobile and readily assimilated in its more soluble forms
- Essential nutrient – therefore <u>can be concentrated to many times levels in ambient media</u>
  - E.g. 24,000X for P-32 uptake in freshwater plants
  - Accumulates in bone and is excreted slowly

Light Metals: K-40

- K-40 is primordial with half-life of 1.3 billion years, gamma emitter
- Homogeneously mixed with stable K
- Widely distributed; accounts for significant fraction of natural background radiation exposure

Light Metals: Cs-137

- Very abundant fission product
- Half-life 27 years: beta and gamma emitter
- Chemical analogue of K
- Mobility and physiological properties have led to detectable concentrations in essentially all organisms
- Uptake correlated with soil properties
  - Soils and sediments of high clay content can immobilize Cs via cation exchange
- Enters plants by aerial deposition or surface adsorption and root uptake
- Enters animals by inhalation, ingestion and surface absorption or adsorption
- Unlike K, Cs concentrations increase with trophic level because it is retained in the body longer

Important Note re Chemical Analogues

- Radionuclide accumulation is reduced if there is an abundance of the analogous element.
- Scarcity usually leads to increased accumulation.
  - E.g. Lower coastal plain of SE USA: low Cs fixing capacity in soils and low available K concentrations – elevated Cs-137 in vegetation and in whitetail deer

Light Metals: Radium-226, 228

- The most important naturally occurring radionuclides in Group IIA
- Daughters of U-238 and th-232
- Ra-226 half life of 1622 yrs, alpha and gamma emitter
- Ra-228 half life of 6.7 years, beta and gamma emitter
- Analogous to Ca; therefore "bone seekers"
- Release from bone very slow; therefore, chronic uptake can lead to comparatively high doses
- Tends to occur in "hot spots"
- Uptake correlated with Ba, sulphate in water and with sediment characteristics
  - Radium does not remain in the water column due to its tendency to co-precipitate as Ba-$RaSO_4$
  - Radium is immobilized by fine-grained sediments with high cation exchange capacity and/or high concentration of iron/manganese oxides
- Does not increase with trophic level due to concentration in bone which is a relatively indigestible "metabolic sink"

Noble Gases: Radon

- Radon-220 and 222 are most significant isotopes – both quite unstable with short half-lives (3.8 days and 55 seconds)
- Behave as true gases and disperse through the atmosphere according to the laws of molecular and turbulent diffusion
- Chemically inert; therefore, transport is not altered by chemical transformations
- Not transported through food chains and do not generally concentrate in biological tissue
    - Exception is Rn-222 which can reside in fatty tissues if generated wtihin an organisms by the decay of radium-226
- Main issue is that radon generates daughter products that are not gaseous and tend to attach to small dust particles – leading to concern regarding inhalation

Heavy Metals: Lead

- 4 lead isotopes produced by radon decay
- Of these lead-210 is the most wide-spread and has the longest half-life (22 years)
- Lead is the heaviest element having stable isotopes and marks the cutoff for alpha emitters – all of which are heavier than lead
- <u>Behaviour similar to the alkaline earths</u>
- <u>Low redox and presence of sulphides reduces uptake from sediments via formation of insoluble lead sulphides</u>
- <u>Major pathway is aerial deposition</u>
  - E.g. Deposition on to lichen in the arctic
- Moderately soluble and retained in the body
  - Leading to accumulation in caribou, humans, wolves

Rare Earths

- Fission products and daughters of fission products
- Stable isotopes of rare earths occur in trace quantities in nature – no known biological role
- Usually form +3 and +2 ions in water
- Mainly form hydroxides and occur as insoluble particulates in water and are adsorbed strongly by soils
- Low biotic uptake and minimal food chain transport
- Readily attach to biological surfaces so may be ingested by filter-feeders
    - Concentrations decrease markedly at higher trophic levels
- Aerial deposition on to vegetation via fallout can occur but would have very low assimilation

Actinides: Uranium

- Actinides are atomic number 89 and above
- All actinides are radioactive
- Natural uranium present in earth's crust at average concentration of about 4 ppm. High-grade ores can be from 1->15%.
- Very low specific activity
- <u>Availability in soil and sediment varies over a wide range according to pH, Eh</u>
- e.g. uranyl ion (UO_2^{2+}) at low pH more readily by plants than carbonate and hydroxyl complexes of U at pH>6

Uranium hydrolysis and redox (JAEA)