Nuclear Data and Society

Long Range Planning Session

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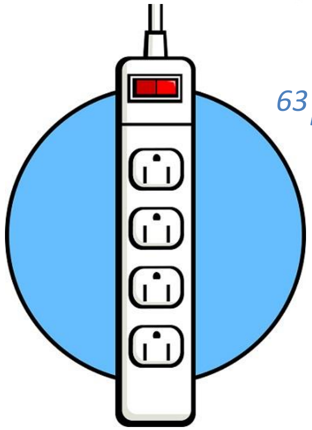
Nuclear isotopes are used in many household items and are pushing the scientific frontier in applications

- Household items
- Industry
- Scientific research

^{85}Kr: *indicator lights on household appliances*

^{241}Am: *fire/smoke alarm*



^{63}Ni: *surge protector*

^{238}U, ^{nat}U, ^{40}K: *Dentures and crowns (<1980's)*

^{229}Th: *Helps fluorescent lights last longer*

^{147}Pm: *electric blanket thermostats*

Criticality Safety
Health Physics
Isotope Biogeochemistry
Isotope Geochemistry
Isotope Hydrology
Nuclear Astrophysics
Nuclear Chemistry
Nuclear Engineering
Nuclear Geophysics
Nuclear Medicine
Nuclear Physics
Radiobiology
Radiochemistry
Radioecology

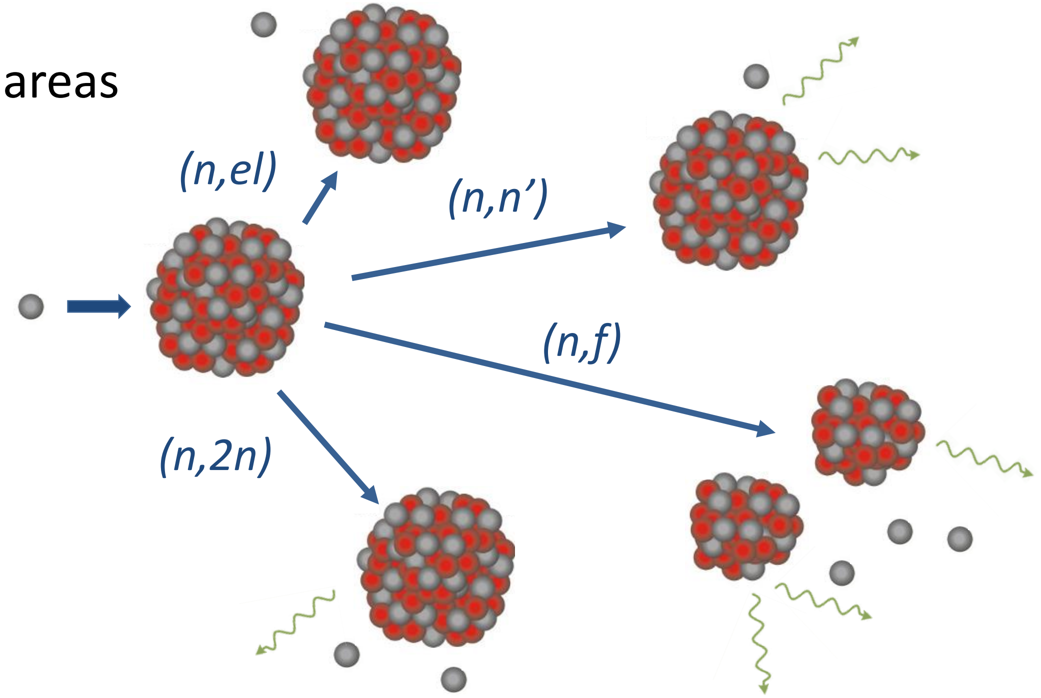
Today will touch on uses, opportunities, and challenges

- Nuclear data are used in many different areas benefitting society – they won't all be covered here, this will be a whirlwind overview

- Some examples will be given, but are not all-encompassing

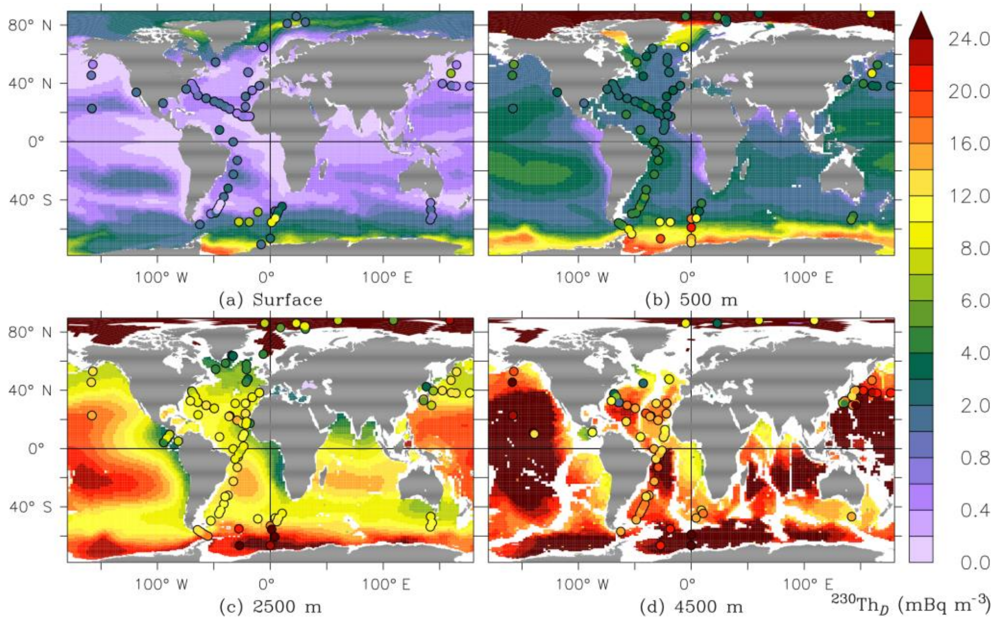
- Utilization of nuclear data can be generally grouped into three areas
  - Chronometers
  - Tracers/signatures
  - Energy deposition and/or production

- Probability for the event and what is produced
  - Radioactive decay half-life, reaction cross section
  - Emissions and products
    - Types
    - Number, multiplicities
    - Energies
    - Angles



Understanding (and improving) our natural world

- Astrophysics
  - Nucleosynthesis and stellar energy generation; *Reactions (cp, n, γ) and decays for stable and unstable*
  - Chronometers/Dating; *^{187}Re, ^{232}Th, ^{235}U, ^{238}U… ^{40}K, ^{87}Rb, ^{138}La, ^{147}Sm, ^{176}Lu*
- Oceanography
  - Food chain contamination; *Co, Ag, Zn, Cd, Hg, ^{137}Cs, ^{210}Po, ^{210}Pb, ^{241}Am*
  - Ocean acidification; *^{13,14}C*
  - Currents and mixing; *^{3}H, ^{14}C, ^{90}Sr, ^{129}I, ^{137}Cs, ^{238,239,240}Pu, ^{241}Am*
- Climate modeling
  - Ice caps/cores*; ^{18}O/^{16}O, ^{2}H/^{1}H, ^{10}Be, ^{36}Cl*
  - Tree rings; *^{13,14}C, ^{226,228}Ra*
- Agriculture
  - Fertilization; *^{15}N, ^{32}P*
  - Radiation-induced mutations; *^{60}Co, β, cp, n, cosmic*
  - Irradiation/food safety; *^{60}Co, ^{137}Cs*



Model of dissolved ^{230}Th activity; Hulten *et al.*, Geosci. Model Dev., 11, (2018) pp 3537–3556 *https://doi.org/10.5194/gmd-11-3537-2018*

Understanding (and improving) our human bodies

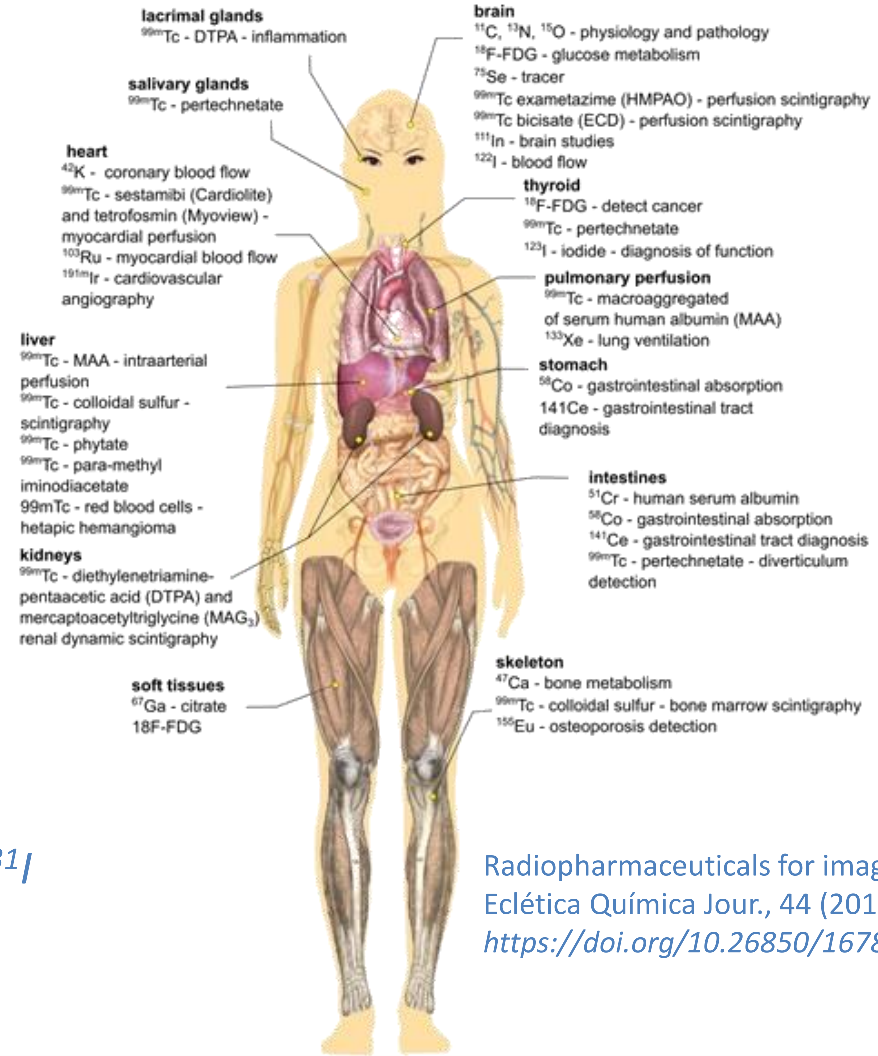
- Irradiation
  - Cancer treatment
    - External beam radiotherapy; *^{60}Co, ^{137}Cs, β, cp, n*
    - Brachytherapy; *^{125}I, ^{131}I, ^{192}Ir*
  - Allograft sterilization; *^{60}Co, ^{137}Cs*

- Diagnostic
  - imaging, PET, SPECT; *^{18}F, ^{68}Ga, ^{82}Rb, ^{99m}Tc, ^{201}Tl*

- Therapeutic
  - Pain relief; *^{89}Sr, ^{153}Sm, ^{186}Re, ^{169}Er*
  - Targeted energy deposition; *^{90}Y, ^{131}I, ^{177}Lu, ^{225}Ac, ^{223}Ra*

- Theragnostic
  - Diagnostic and therapeutic; *^{64}Cu-^{67}Cu, ^{43,44}Sc-^{47}Sc, ^{123}I-^{131}I*

- Historical pacemaker, *^{238}Pu*



Radiopharmaceuticals for imaging; Payolla *et al.*, Eclética Química Jour., 44 (2019) pp 11–19
https://doi.org/10.26850/1678-4618eqj.v44.3.2019.p11-19

Reaching out (or in) to the unknown

- Radioisotope thermionic power; *^{90}Sr, ^{238}Pu, ^{241}Am, ^{244}Cm*
  - Heat from radioactive decay
  - Arctic, ocean floor, space…
- Terrestrial exploration
  - Geochronometers; *^{235,238}U > ^{207,206}Pb, ^{187}Re-^{187}Os, ^{40}Ar/^{39}Ar*
  - Moon formation; *^{182}Hf-^{182}W, ^{146}Sm-^{142}Nd, and ^{176}Lu-^{176}Hf*
  - Isotope hydrology, water age/origins; *^{3}H, ^{14}C, ^{81}Kr, ^{4}He*
  - Geologic characterization; *NAA, PGAA, XRF, PIXE, PIGE, NMR*
- Extraterrestrial and meteoritic composition
  - Chondrites and chondrules; *U/Pb ratios, ^{26}Al-^{26}Mg*
  - Iron meteorites; *^{182}Hf-^{182}W*
  - Achondrites, angrites; *^{53}Mn/^{55}Mn*
  - Characterization
    - asteroid Psyche; *γ-spectroscopy*
    - Saturn moon Titan; *neutron activation, γ-spectroscopy*

TABLE I. Physical properties, abundance and occurrence of the geologically important radioactive elements.

Element	Active isotope	Radiations	Energy in Mev	Decay constant λ in sec.$^{-1}$	Half-period T	‡Mean abundance of active isotope g/g rock	Occurrence
Potassium	K^{40} K^{40}	β γ	1.2 2.0	$1.4\pm0.3\times10^{-17}$ 4×10^{-19}	$1.6\pm0.3\times10^{9}y$ $5\times10^{10}y$	$2.2\pm0.4\times10^{-6}$	Rocks, evaporites, and sea-water.
Rubidium	Rb^{87}	β	0.13	$3.5\pm1\times10^{-19}$	$6.3\pm2\times10^{10}y$	ca 6×10^{-6}	Lepidolite and other Li-bearing minerals.
Samarium	Sm^{148}	α	2.55	2.5×10^{-19}	$0.9\times10^{11}y$	ca 10^{-6}	Samarskite, cerite and monazite.
Radon	Rn Tn An	α α α	5.49 6.28 6.82	2.10×10^{-6} 1.27×10^{-2} 0.177	$3.82d$ $54.5s$ $3.92s$	ca 3×10^{-18} ca 7×10^{-22} ca 2×10^{-24}	Genetically associated with uranium, thorium, and actino-uranium, respectively, in rocks, radioactive minerals, atmosphere, mineral waters, and sea water.
Radium	Ra ThX	α α	4.87 5.78	1.4×10^{-11} 2.20×10^{-6}	$1600y$ $3.64d$	$0.5\pm0.1\times10^{-12}$ ca 4×10^{-18}	Genetically associated with uranium and thorium, respectively, also found separately in certain mineral springs.
Thorium	Th RdTh Io	α α α	4.31 5.47 4.66	1.58×10^{-18} 1.16×10^{-8} 3×10^{-13}	$1.40\times10^{10}y$ $1.9y$ $8\times10^{4}y$	$5.6\pm1\times10^{-6}$ ca 8×10^{-16} ca 3×10^{-11}	Rocks, monazite, thorite, and thorianite. Ionium genetically associated with uranium.
Protactinium	Pa	α	5.1	7.0×10^{-13}	$3.1\times10^{4}y$	ca 4×10^{-13}	Genetically associated with actino-uranium (U^{235}).
Uranium	U^{238} U^{235}	α α	4.13 4.4	4.87×10^{-18} $3.1\pm0.1\times10^{-17}$	$4.52\times10^{9}y$ $7.1\pm0.3\times10^{8}y$	$1.4\pm0.3\times10^{-6}$ 1.0×10^{-8}	Rocks, uraninite pitchblende and carnotite.

Nuclear geophysics is a mature field where the use of isotopes was recognized early; Goodman, J. of Appl. Physics 12 (1942) pp 276 - 289
https://doi.org/10.1063/1.1714866

Industrial applications utilize decays and reactions

- Nuclear densitometry; *^{137}Cs, ^{226}Ra, ^{241}Am/Be*
  - Nuclear logging, Measurement While Drilling, Logging While Drilling
  - Identify oil deposits, porosity, water content of coal
  - Construction, soil compaction and asphalt

- Oil and gas tracing; *^{24}Na, ^{56}Mn, ^{110m}Ag, ^{131}I, ^{133}Xe, ^{140}La*

- Processing; *^{82}Br, ^{137}Cs, ^{109}Cd, ^{192}Ir, ^{244}Cm*
  - Flow, blending, separation of materials
  - Automatic control of filling furnaces, vessels, transport containers

- Materials characterization
  - Construction, e.g. welds, wear, damage effects, shielding; *^{137}Cs, ^{60}Co, ^{192}Ir*
  - Contamination, mining, processing, and smelting or uranium, phosphate, lead and iron ore, burning fossil fuels (coal), and burning leaded gasoline; *^{238}U and ^{232}Th decay series (^{210}Pb, ^{210}Po), Rn gas*

- Transmutation, e.g. doping Si semiconductors; *reactor n (fission)*

Paper/board weight using ^{85}Kr or ^{147}Pm (Beta-emitters)
https://jasch.net.in/paper-global-trendsetting-technology

Nuclear reactors provide power

- Electrical generation
  - 437 operating power reactors, 57 under construction, 102 planned (Sept 2022); mostly Pressurized Water Reactor (PWR)
  - Higher burn-up, modified fuels proposed
- Propulsion
  - aircraft carriers, nuclear submarines, ice breakers
  - space
    - Nuclear Thermal Propulsion (NTP)
    - Nuclear Electric Propulsion (NEP)
- Future Reactors
  - Small Modular Reactors, 50+ concepts*;*

    fast neutron reactions, materials, dynamics
  - Fusion Reactors; *cp fusion*
- Safeguards
  - Material control and accounting
  - Characterization

Fission, fission product decays and reactions, neutron absorption and moderation reactions, n and γ production and transmission/shielding, half-lives…

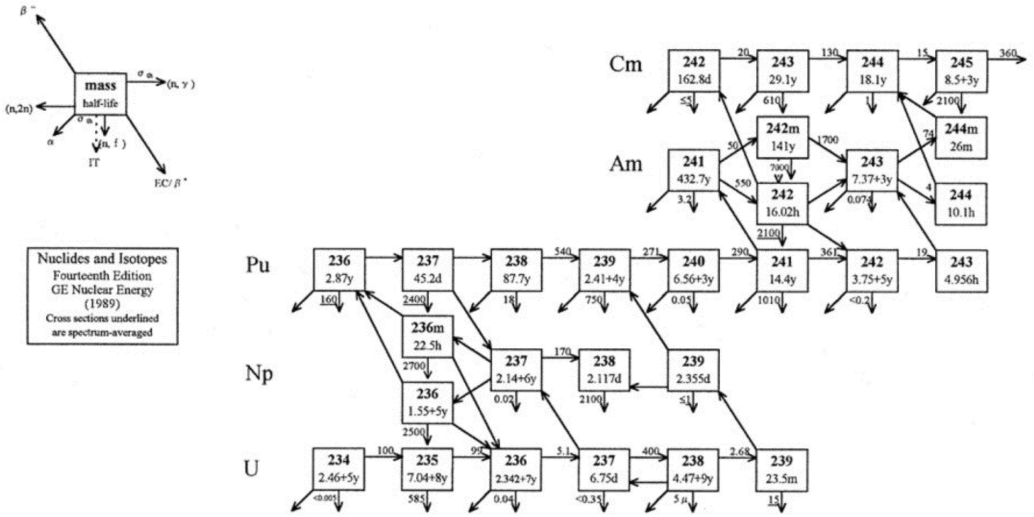


FIG.III-3. Actinide transmutation chains for UO_2 and MOX fuel (detail).

A large number of complex reaction networks in the fuel and other materials must be considered; Nuclear Fuel Cycle Simulation System: Improvements and Applications, IAEA-TECDOC-1864

Nuclear security considers nuclear threats

- Non-proliferation: prevent the spread of nuclear weapons
  - Detect, characterize, monitor nuclear fuel cycle activities
  - Detect the illicit movement of nuclear materials
- Counterterrorism and counterproliferation
  - Counter acquisition of nuclear capabilities
  - Respond to nuclear and radiological incidents
- Forensics
  - Determine origin of materials outside of regulatory control
  - Respond to nuclear and radiological incidents
- Stockpile stewardship
  - Expand predictive capability
  - Maintain deterrence

Fission, fission product decays and reactions, neutron reactions, cp reactions, n and γ production and transmission/shielding, half-lives…

Radiation portal monitor
https://en.wikipedia.org/wiki/Radiation_portal_monitor

"Cop with scary gadget", blog of Zack Hample, 2008
https://mlblogssnaggingbaseballs.wordpress.com/2008/07/17/2008-home-run-derby

Opportunities and challenges in nuclear applications

- The use of nuclear reactions and radioisotopes has many significant advantages
  - Security can be gained: nuclear, energy, food, and water
  - Scientific understanding of complex processes can be undertaken - fact-based findings can support policymakers, e.g. pollution control, public safety
  - Information and controls can provide significant cost and time savings, as well as safety

- Most applications are multidisciplinary
  - Utilization of nuclear science techniques often requires training and knowledge
  - What can we do to support the next generation in connecting fields?

- Risk
  - Regulations and controls can inhibit use of radioactive materials
  - What can we do to properly understand and communicate the risk/reward balance?

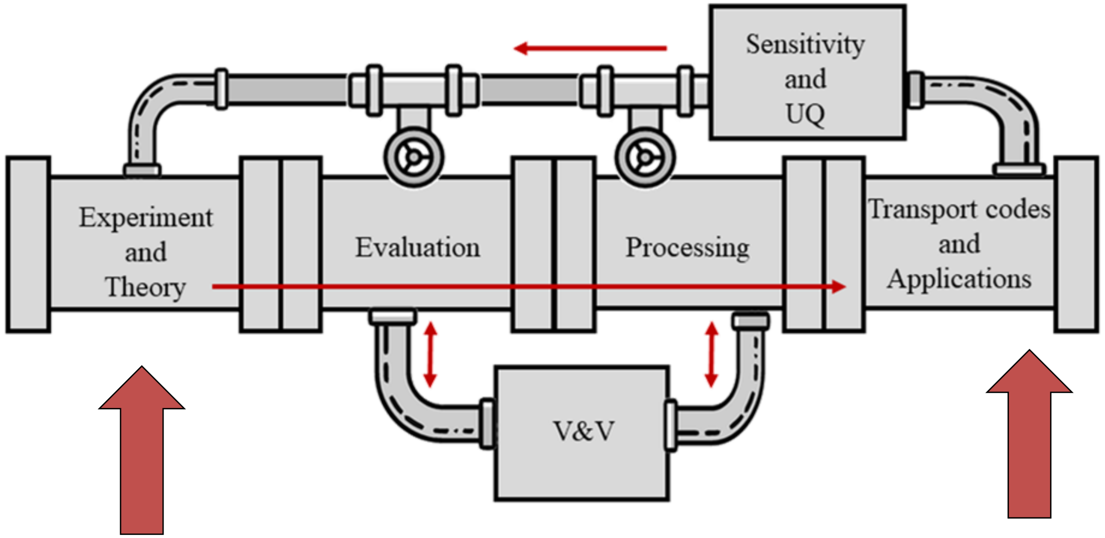
- Most applications rely on simulation and modeling
  - Do we have the necessary data readily available?

I think we can do better!

New data are needed, with improved timelines for delivering to applications

- Experiments and Theory are pushing the scientific boundaries
  - New experimental facilities, complex detector arrays
  - Sophisticated algorithms, analyses
  - Larger computation platforms, GPU capabilities
- Data needs
  - Reactions on unstable isotopes
  - Quantified uncertainties; precision improvements may need integral or quasi-integral data
  - Nuclear structure and decay data with reaction data
- Evaluation capabilities
  - Rate-limiting step
  - Modern tools and infrastructure
  - Peoplepower

Nuclear data pipeline



Foundational Sciences

Applications

Nuclear data are shared: different applications use the same data resource

Multiple applications rely on nuclear data

- Six examples of applications fields
  - Environmental sciences
  - Medical physics
  - Geophysical characterization
  - Industrial applications
  - Nuclear power
  - Nuclear security
- Multidisciplinary
- Difficult environments –
  - Underwater, underground, outer space
  - Extreme temperatures, pressures
- Challenging observations/detection… and interpretation

The nuclear science community "owns" part of the problem space:

- Can we produce new tracer or medical isotopes? Can we calculate the production accurately?
- Do we understand the nuclear reaction networks in high flux environments?
- Do we know the reaction and decay products accurately?
- Are these data accessible for modeling/simulation?
- Do we have detection techniques that could be applied in the field?

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Naturally occurring isotopes from U and Th series

Element	U-238 series							Th-232 series					U-235 series				
Neptunium																	
Uranium	U-238 4.47×10^9 y		U-234 2.48×10^5 y										U-235 7.04×10^8 y				
Protactinium		Pa-234 1.18 min												Pa-231 3.25×10^4 y			
Thorium	Th-234 24.1 d		Th-230 7.52×10^4 y					Th-232 1.40×10^{10} y		Th-228 1.91 y			Th-231 25.5 hrs		Th-227 18.7 d		
Actinium									Ac-228 6.13 hrs					Ac-227 21.8 y			
Radium			Ra-226 1.62×10^3 y					Ra-228 5.75 y		Ra-224 3.66 d					Ra-223 11.4 d		
Francium																	
Radon			Rn-222 3.82 d							Rn-220 55.6 s					Rn-219 3.96 s		
Astatine																	
Polonium			Po-218 3.05 min		Po-214 1.64×10^{-4} s		Po-210 138 d			Po-216 0.15 s	64%	Po-212 3.0×10^{-7} s			Po-215 1.78×10^{-3} s		
Bismuth				Bi-214 19.7 min		Bi-210 5.01 d					Bi-212 60.6 min					Bi-211 2.15 min	
Lead			Pb-214 26.8 min		Pb-210 22.3 y		Pb-206 Stable lead isotope			Pb-212 10.6 hrs	36%	Pb-208 Stable lead isotope			Pb-211 36.1 min		Pb-207 Stable lead isotope
Thallium											Tl-208 3.05 min					Tl-207 4.77 min	