Chemical Engineering 412

Introductory Nuclear Engineering

Lecture 8 Nuclear Decay in Nature



The BIG Picture





Spiritual Thought

Peering into the sealing room in the Los Angeles California Temple where she and her now-deceased husband, Winston, were married more than 50 years ago brings peace to Sally Smith...

"After a lifetime of being together, my dear Win and I are now separated by a painful parting. Nevertheless, through the Savior's atoning sacrifice and the reality of the sealing power of the priesthood, I feel hope—even joy—during this trying season of my life, knowing we will one day be together again."



Thorium Decay Chain (4n)



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Uranium Decay Chain (4n+2)





Actinium Decay Chain (4n+3)



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4 Possible decay chains



Mass number given by 4n (²³²Th), 4n+2 (²³⁸U or ²³⁴Np), and 4n+3 (²³⁵U or ²³⁹Pu) are near secular equilibrium. 4n+1 (²⁴¹Ac/Pu) has no step slow enough. Radioisotopes from it have long since decayed and are not found in nature.



Carbon-14 (Organic) Dating



Living materials consume atmospheric carbon with fixed ¹⁴C/¹²C ratios. At death, ¹⁴C decays to N but ¹²C does not, so the ratio changes.

Assuming constant atmospheric concentration of ¹⁴C

$$t = -\frac{1}{\lambda} \ln\left(\frac{N(t)}{N(0)}\right) = -\frac{1}{\lambda} \ln\left(\frac{N(t)/N_s}{N(0)/N_s}\right) = -\frac{1}{\lambda} \ln\left(\frac{A_{14}(t)/g(C)}{A_{14}(0)/g(C)}\right)$$



Carbon Dating Continued

- Atmospheric ratios of ¹⁴C to ¹²C is about 1.23x10⁻¹²
 - Measured as ¹⁴C activity per gram of (total) carbon
 - $\bullet \quad \frac{A_{14}}{\langle n \rangle} = \frac{N_{14}}{N_{14}} \frac{\lambda_{14} N_a}{\lambda_{14}}$
 - $g(C) = N_{12} = 12$
 - yields 0.237 Bq/g(C) or 6.4 pCi/g(C)

Major sources of error:

- 1. Cosmic ray/magnetosphere intensity variations: ¹⁴C
- 2. Half-life for¹⁴C of 5568 years (originally) actually 5730 yrs
- 3. Solar Activity/Global Temperature affects carbon exchange between rocks, ocean, and air
- 4. Natural Variation in ¹²C (volcanos, photosynthesis, etc.)
- 5. Human increases in ¹²C
 - Fossil combustion

BYU

Atmospheric nuclear testing

Rock (Inorganic) Ages

 $N_1(t) = N_1(0)e^{-\lambda t}$ No initial amount of product in $N_2(t) = N_1(0)[1 - e^{-\lambda t}]$ formation.

$$t = -\frac{1}{\lambda_1} \ln\left(1 + \frac{N_2(t)}{N_1(t)}\right)$$

$$N_1(t) = N_1(0)e^{-\lambda t}$$
$$N_2(t) = N_2(0) + N_1(0)[1 - e^{-\lambda t}]$$

Initial amount of stable isotope $N'_2(t)$. R(t) is ratio of $N_2(t)/N'_2(t)$.

$$t = -\frac{1}{\lambda_1} \ln \left\{ 1 + \frac{N_2'(t)}{N_1(t)} [R(t) - R_0] \right\}$$



Three-component Decays

$$X_1 \to X_2 \to X_3$$

$$N_{1}(t) = N_{1}^{0} \exp(-\lambda_{1}t)$$
$$N_{2}(t) = N_{2}^{0} \exp(-\lambda_{2}t) + \frac{\lambda_{1}N_{1}^{0}}{\lambda_{2} - \lambda_{1}} \left[\exp(-\lambda_{1}t) - \exp(-\lambda_{2}t)\right]$$
$$N_{3}(t) = N_{3}^{0} + N_{2}^{0} \left[1 - \exp(-\lambda_{2}t)\right] + \frac{1}{\lambda_{2}^{0} - \lambda_{1}} \left[\lambda_{2}(1 - \exp(-\lambda_{1}t)) - \lambda_{1}(1 - \exp(-\lambda_{2}t))\right]$$

Assumes stable third component but otherwise general.



Three-isotope Series



OUNG

Daughter Particle Dynamics



Reactive Daughter

Lethargic Daughter

- Dashed line is parent concentration
- All calculations presume 0 initial daughter concentration
- Equilibrium assumption better as daughter reactivity increases.



Analysis of SS and Partial Equilibrium Assumptions

Apply SS assumption to species B in the sequence

 $A \xrightarrow{k_{fA}} B \xrightarrow{k_{fB}} C$

concentrations are given by two differential and one algebraic equation

$$\frac{dC_A}{dt} = -k_A C_A$$
$$\frac{dC_B}{dt} = k_A C_A - k_B C_B = 0$$
$$\Rightarrow C_B = \frac{k_A}{k_B} C_A$$



$$\frac{dC_{C}}{dt} = k_{B}C_{B}$$

The analytical solutions to these reactions are as follows:

$$\frac{C_A}{C_{A0}} = \exp(-k_A t)$$
$$\frac{C_B}{C_{A0}} = \frac{k_A}{k_B} \exp(-k_A t)$$
$$\frac{C_C}{C_{A0}} = 1 - \exp(-k_A t)$$

Comparison of Anal. Vs. Simplified





For reaction rate coefficients k_A and k_B that differ by a factor of .5, errors in mass conservation and species C & B concentrations are large.

Mole Concentration/[A]₀

Comparison of Anal. Vs. Simplified



For nearly comparable reaction rate coefficients k_A and k_B, errors in mass conservation persist well beyond the initial transient. Species C and, to a lesser extent, B are also in error.

Comparison of Anal. Vs. Simplified





For reaction rate coefficients k_A and k_B that differ by a factor of 5, errors in mass conservation and species C concentrations still persist beyond the initial transient.

Transient Equilibrium



For reaction rate coefficients k_A and k_B that differ by a factor of 10 (or more), small errors in mass conservation and species C concentrations persist beyond initial transient.

Lessons learned

- Simplifying assumptions:
 - Steady-state (SS) partial equilibrium (PE)
 - Do not lead to non-changing concentrations of species
 - violate the laws of mass conservation
- Violation consequences are not important:
 - Concentrations of species involved are small (nearly all radicals)
 - Relative reaction rates differ by orders of magnitude.
- Otherwise, large errors if SS and PE assumptions are applied



Isobars w/ 1 Stable Isotope





Isobars w/ 2 Stable Isotopes





Isobars w/ 3 Stable Isotopes



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Radon Issues

- Essentially all radon exposure is from ²²²Rn – primarily from its progeny. Other isotopes have much shorter half lives and/or are produced in lower quantities in natural decay.
- EPA estimates that radon is the second leading cause of lung cancer in the US (after smoking).
- EPA recommends remediation in homes with radon levels above 4 pCi/l.

RADON-HAZARD POTENTIAL IN THE PROVO-OREM AREA, UTAH COUNTY, UTAH



This map shows the radon-hazard potential based on geologic factors. This map is for general reference only. Indoorradon levels can be strongly affected by non-geologic factors such as weather, lifestyle, and building construction and maintenance. The only way to accurately determine the indoor-radon level within a specific building is to test.



Uranium Ore Secular Equilibrium



The radiation is virtually trapped underground; exposures are only possible if contaminated groundwater, that is circulating through the deposit, is used for drinking. Radon is of no concern for deep deposits, though it can travel through underground fissures, since it decays before it can reach the surface.

The situation changes completely, when the deposit is mined: <u>Radon</u> gas can escape into the air, ore dust can be blown by the wind, and contaminants can be leached and seep into surface water bodies and groundwater.



Source: Wise Uranium Project, http://www.wise-uranium.org/rup.html

Natural Uranium



Initially, it only contains the uranium isotopes. Within a few days, Th-231 (U-235 series), and within a few months, Th-234 and Pa-234m (U-238 series) grow in. The activity then remains stable for more than 10,000 years. After this time, Th-230 and all other decay products of the U-238 series, and Pa-231 and all other decay products of the U-235 series grow in. This could, however, only occur with residual ore concentrate not consumed for nuclear fuel production

Source: Wise Uranium Project, http://www.wise-uranium.org/rup.html