Chapter 11

Nuclear Chemistry

1. Indicate the number of neutrons in each of the following nuclei.

	A	Z	N = A-Z
a) ^{10}**Be**	10	4	6
b) ^{100}**Mo**	100	42	58
c) ^{75}**As**	75	33	42
d) ^{197}**Au**	197	79	118

3. Write the symbol, including atomic number and mass, for each of the following isotopes.

a) Z = 26, A = 56 $^{56}_{26}Fe$ **b) A = 74, N = 40** $^{74}_{34}Se$ **c) Z = 54, N = 78** $^{132}_{54}Xe$

5. There are three naturally occurring isotopes of silicon. Use the data below to determine the atomic mass of Si.

	Mass(amu)	Abundance
^{28}Si	27.97693	92.21%
^{29}Si	28.97649	4.70%
^{30}Si	29.97376	3.09%

One mole of naturally occurring silicon contains:

(0.9221 mole ^{28}Si)(27.97693 g/mol) + (0.0470 mol ^{29}Si)(28.94649 g/mol) + (0.0309 mol ^{30}Si)(29.97376 g/mol) or 28.086 g Si

7. The natural abundance of deuterium, $^{2}_{1}H$, is 0.015%. How many deuterium nuclei are in 100. mL of water?

$$100\text{ g }H_2O \times \frac{1\text{ mol }H_2O}{18.0\text{ g }H_2O} \times \frac{6.02\times10^{23}\text{ molecules}}{\text{mol }H_2O} \times \frac{2\text{ H atoms}}{H_2O\text{ molecule}} \times \frac{1.5\times10^{-2}\text{ D atom}}{100\text{ H atom}} = 1.00\times10^{21}\text{ D atoms}$$

9. Determine the mass defects (in kg per mole) for the following nuclei.

$m_{atom} = M_m - Z(0.00055)$; $m_{nucleons} = Z(1.00728) + N_n(1.00867)$; $\Delta m = m_{nucleons} - m_{atom}$

Atom	A	Z	N_n	M_m	Δm in g	Δm in kg
Br	79	35	44	78.9183	0.7373	7.373×10^{-4}
Ru	99	44	55	98.9061	0.9153	9.153×10^{-4}

11. What are the binding energies and binding energies per nucleon for each of the nuclei in Exercise 9?

	ΔE (kJ) = $\Delta mc^2/1000$	ΔE (kJ)/A
a) Br	6.6262×10^{10}	8.3876×10^{8}
b) Ru	8.2265×10^{10}	8.3095×10^{8}

13. Which nucleus in Exercise 9 is thermodynamically more stable?

Nucleus with greater ΔE/A is ^{79}Br as shown in Exercise 11.

15. Predict the mode of decay for each of the following.

	Z	N	N/Z	mode of decay
a) ^{233}**U**	92 > 83	141	1.53 (ok)	α-decay
b) ^{197}**Pb**	82 < 83	115	1.40 (low)	β^+ emission or EC (actually EC)
c) ^{231}**Ac**	89 > 83	142	1.59 (high)	β^- decay
d) ^{225}**Th**	90 > 83	135	1.50 (ok)	α-decay

17. Identify X in each of the following nuclear reactions.

a) $^{144}Nd \rightarrow {}^{140}Ce + X$ $\qquad {}^{144}_{60}Nd \rightarrow {}^{140}_{58}Ce + {}^{4}_{2}X \Rightarrow X = {}^{4}He$

b) $^{238}U + n \rightarrow 3n + {}^{81}Ge + X$ $\qquad {}^{238}_{92}U + {}^{1}_{0}n \rightarrow 3\,{}^{1}_{0}n + {}^{81}_{32}Ge + {}^{155}_{60}X \Rightarrow X = {}^{155}Nd$

c) $^{16}O + \alpha \rightarrow X$ $\qquad {}^{16}_{8}O + {}^{4}_{2}\alpha \rightarrow {}^{20}_{10}X \Rightarrow X = {}^{20}Ne$

19. Write complete nuclear reactions for the following:

a) Potassium-40 undergoes beta decay. $\qquad {}^{40}_{19}K \rightarrow {}^{0}_{-1}\beta + {}^{40}_{20}Ca$

b) Chlorine-34 emits a positron. $\qquad {}^{34}_{17}Cl \rightarrow {}^{0}_{1}\beta^{+} + {}^{34}_{16}S$

c) Arsenic-73 undergoes electron capture. $\qquad {}^{73}_{33}As + {}^{0}_{-1}e \rightarrow {}^{73}_{32}Ge$

d) Bismuth-214 decays to thallium-210 $\qquad {}^{214}_{83}Bi \rightarrow {}^{210}_{81}Tl + {}^{4}_{2}He$

21. Radon-222 undergoes the following decay sequence to a stable nucleus: α, α, β, β, α, β, β, α. What is the identity of the resulting nucleus?

$$^{222}_{86}Rn \xrightarrow{\alpha} {}^{218}_{84}Po \xrightarrow{\alpha} {}^{214}_{82}Pb \xrightarrow{\beta} {}^{214}_{83}Bi \xrightarrow{\beta} {}^{214}_{84}Po \xrightarrow{\alpha} {}^{210}_{82}Pb \xrightarrow{\beta} {}^{210}_{83}Bi \xrightarrow{\beta} {}^{210}_{84}Po \xrightarrow{\alpha} {}^{206}_{82}Pb$$

23. ^{239}Pu is a very toxic material used in nuclear weapons. If its half-life is 2.44 x 10^4 years. How long will a sample of Pu have to be stored before only 1% of the original sample remains?

$$k = \frac{0.693}{2.44\times10^{4}} = 2.84\times10^{-5}\ yr^{-1} \Rightarrow \ln(0.01) = -2.30 = -(2.84\times10^{-5}\ yr^{-1})t \Rightarrow t = \frac{4.60}{2.84\times10^{-5}} = 162{,}000\ yr$$

25. A 12.30-mg sample of ^{47}Ca is found to contain 3.24 mg of ^{47}Sc after 2.00 days, what is the half-life of ^{47}Ca in days? What type of decay does ^{47}Ca undergo?

The reaction is $^{47}Ca \rightarrow {}^{47}Sc + \beta$

^{47}Sc and ^{47}Ca have the same atomic mass, so the formation of 3.24 mg of ^{47}Sc means the decay of 3.24 mg of ^{47}Ca. The amount of ^{47}Ca that remains after two days is 12.30 – 3.24 = 9.06 g

$$\ln\frac{N}{N_o} = \ln\frac{9.06}{12.30} = \ln 0.737 = -0.306 = -kt = -k(2.00), \text{ so } k = \frac{-0.306}{-2.00} = 0.153\ day^{-1} \text{ and } t_{1/2} = \frac{\ln 2}{0.153} = 4.53\ days$$

27. The Shroud of Turin is a long linen cloth that bears an image of a bearded, longhaired man, with numerous lacerations over his body. Tradition, dating back to the fourteenth century, has it that the fabric is the burial shroud of Jesus Christ. In 1988, its age was determined by carbon dating. If a fiber of the shroud had a ^{14}C disintegration rate of 14.0 d·min^{-1}·g^{-1}, how old was the cloth.

$$\ln\frac{N}{N_o} = \ln\frac{14.0}{15.3} = -0.0888 \Rightarrow k = \frac{\ln 2}{t_{1/2}} = \frac{0.693}{5730\ yr} = 1.21\times10^{-4}\ yr^{-1}$$

$$-0.0888 = -(1.21\times10^{-4}\ yr^{-1})t \Rightarrow t = \frac{-0.0888}{-1.21\times10^{-4}\ yr^{-1}} = 734\ years$$

What conclusion can be drawn about the authenticity of the claim that it is the burial cloth of Jesus Christ?

This result implies that the flax was harvested during the Middle Ages (14th century), which would imply that the shroud could not have been the shroud of Jesus Christ. However, other scientists have argued that the disintegration rate is so high because the fiber had bacteria and fungi attached to it. If these bacteria and fungi died recently, the count would be raised considerably.

29. How old is a rock sample from a meteor if it contains 73.2 mg of ^{238}U and 20.2 mg of ^{206}Pb. Assume that all of the ^{206}Pb was formed from ^{238}U. The half-life of the $^{238}U \rightarrow {}^{206}Pb$ process is 4.5×10^9 years.

The two masses cannot be used directly in Equation 11.6 because the atomic masses are different. Consequently, we must first convert both masses to moles.

$$73.2\text{ mg }^{238}U \times \frac{1\text{ mmol }^{238}U}{238\text{ mg }^{238}U} = 0.308\text{ mmol }^{238}U \qquad 20.2\text{ mg }^{206}Pb \times \frac{1\text{ mmol }^{206}Pb}{206\text{ mg }^{206}Pb} = 0.0981\text{ mmol }^{206}Pb$$

N = mmoles of ^{238}U still present = 0.0981 mmol

N_o = initial mmoles of ^{238}U = mmol ^{238}U present + mmol ^{238}U reacting

N_o = mmol ^{238}U + mmol ^{206}Pb = 0.308 + 0.098 = 0.406 mmol

$$\ln\frac{N}{N_o} = \ln\frac{0.00981}{0.406} = -1.42 \qquad \& \qquad k = \frac{\ln 2}{t_{1/2}} = \frac{0.693}{4.5\times10^{9}\text{ yr}} = 1.5\times10^{-10}\text{ yr}^{-1}$$

$$-1.42 = -(1.5\times10^{-10}\text{ yr}^{-1})t \qquad \Rightarrow \qquad t = \frac{-1.42}{-1.5\times10^{-10}\text{ yr}^{-1}} = 9.3\times10^{9}\text{ years}$$

31. List beta particles, gamma rays and alpha particles in order of increasing penetrating power. $\alpha < \beta < \gamma$

33. Determine the mass defect in kilograms of each of the following reactions.

a) $2\,^{12}C \rightarrow {}^{24}Mg$ $\quad \Delta m = 23.9850 - 2 \times 12.0000 = -0.0150\text{ g} = -1.50 \times 10^{-5}\text{ kg}$

b) $^{238}U \rightarrow {}^{234}Th + \alpha$ $\quad \Delta m = 234.0436 + 4.0026 - 238.0508 = -0.0046\text{ g} = -4.6 \times 10^{-6}\text{ kg}$

c) $\beta^+ + \beta^- \rightarrow \gamma$ $\quad \Delta m = 0 - 2(0.000549) = -0.001098\text{ g} = -1.098 \times 10^{-6}\text{ kg}$

d) $^{239}Pu + {}^{4}He \rightarrow {}^{242}Cm + n$ $\quad \Delta m = 242.0588 + 1.00867 - 239.0522 - 4.0026 = +0.01267\text{ g} = +1.267 \times 10^{-5}\text{ kg}$

35. What is the energy change of each reaction listed in Exercise 33?

Use the answers in Exercise 33 and Equation 11.4, $\Delta E = \Delta mc^2$, $c = 2.998 \times 10^8$ m/s

a) $2\,^{12}C \rightarrow {}^{24}Mg$ $\quad \Delta E = (-1.50 \times 10^{-5}\text{ kg})(2.998 \times 10^8\text{ m/s})^2 = -1.35 \times 10^{12}\text{ J} = -1.35 \times 10^9\text{ kJ}$

b) $^{238}U \rightarrow {}^{234}Th + \alpha$ $\quad \Delta E = (-4.6 \times 10^{-6}\text{ kg})(2.998 \times 10^8\text{ m/s})^2 = -4.1 \times 10^{11}\text{ J} = -4.1 \times 10^8\text{ kJ}$

c) $\beta^+ + \beta^- \rightarrow \gamma$ $\quad \Delta E = (-1.098 \times 10^{-6}\text{ kg})(2.998 \times 10^8\text{ m/s})^2 = -9.869 \times 10^{10}\text{ J} = -9.869 \times 10^7\text{ kJ}$

d) $^{239}Pu + {}^{4}He \rightarrow {}^{242}Cm + n$ $\quad \Delta E = (1.267 \times 10^{-5}\text{ kg})(2.998 \times 10^8\text{ m/s})^2 = 1.139 \times 10^{12}\text{ J} = 1.139 \times 10^9\text{ kJ}$

37. Classify each reaction in Exercise 33 as fission, fusion, decay or annihilation. If it is a decay, indicate what kind.

a) fusion **b)** decay (α) **c)** annihilation **d)** fusion

39. What is a chain reaction? How is the chain reaction in a nuclear power plant controlled? See Section 11.5