Section 14: Nuclear Chemistry

The following maps the videos in this section to the Texas Essential Knowledge and Skills for Science TAC §112.35(c).

14.01 Radioactive Decay
- Chemistry (12)(A)
- Chemistry (12)(B)

14.02 Nuclear Stability
- N/A

14.03 Nuclear Fission and Nuclear Fusion
- Chemistry (12)(C)

Note: Unless stated otherwise, any sample data is fictitious and used solely for the purpose of instruction.

14.01

Radioactive Decay

Radioactivity or ***radioactive decay*** is the spontaneous emission of rays or particles from certain elements, such as plutonium. The rays or particles emitted from the radiation source are called ***nuclear radiation***.

Chemical and nuclear reactions occur because certain atomic configurations are unstable and naturally give way to more stable atoms. Nuclear reactions begin with ***radioisotopes***, which are unstable isotopes.

- Radioisotopes undergo changes in their nuclei to become stable.
- Unlike chemical reactions, nuclear reactions are not affected by changes in pressure or temperature or by the presence of catalysts.
- Nuclear reactions of a given unstable isotope cannot be slowed down, sped up, or stopped.

The spontaneous process of radioactive decay does not require an input of energy. Once an unstable isotopes decays, the process is not completed until a stable isotope is reached.

- During radioactive decay, the isotope emits radiation.
- There are three types of nuclear radiation:
    - ***Alpha radiation*** (α) has low penetrating power. It cannot penetrate past clothing or a few sheets of paper.
    - ***Beta radiation*** (β) has moderate penetrating power. It can pass through paper but is stopped by aluminum foil or thin pieces of wood.
    - ***Gamma radiation*** (γ) has very high penetrating power. It can penetrate the body completely.

Characteristics of Alpha, Beta, and Gamma Radiation				
Type	**Consists of**	**Symbols**	**Charge**	**Penetrating power**
Alpha radiation	Alpha particles (helium nuclei)	${}^{4}_{2}He$, α	+2	Low
Beta radiation	Beta particles (electrons)	${}^{0}_{-1}e$, β	-1	Moderate
Gamma radiation	High-energy electromagnetic radiation	γ	0	Very high

Nuclear Equation

A ***nuclear equation*** is a way of expressing a nuclear reaction in writing.

- The symbols of the reactants are connected by an arrow to the symbols of the products.
- A balanced nuclear equation is also used to describe radioactive decay, with the sum of the mass and atomic numbers on the right equal to the sum of the mass and atomic numbers on the left.

$$^{28}_{15}P \rightarrow \; ^{0}_{-1}\beta \; + \; ^{28}_{16}S$$

- Alpha and beta particles will alter the mass number and atomic number of nuclei, while a gamma particle does not alter the nuclei. Instead, gamma radiation will emit high-energy electromagnetic radiation, which is very dangerous.

1. Write the nuclear reaction for the radioactive decay of radon-219 when two beta particles, one gamma particle, and three alpha particles are emitted to produce a stable isotope.

2. Write a balanced nuclear equation for the radioactive decay of $^{47}_{20}Ca$ to $^{47}_{21}Sc$.

14.02

Nuclear Stability

The stability of a nucleus depends on the ratio of neutrons to protons. The closer that ratio is to 1, the more stable it is. A graph of neutrons and protons will produce a ***band of stability***, which describes the number of stable isotopes that are available for all atoms.

- All stable isotopes with 20 protons or fewer (up to calcium) have a ratio of neutrons to protons equal to 1.
- After calcium, all isotopes have a ratio of neutrons to protons greater than 1.
- Beyond bismuth, there are many unstable isotopes.
- The heavier the unstable nuclei, the shorter the lifetime of the element.
- Elements with an even number of protons have a greater number of stable isotopes than elements with an odd number of protons.

The neutron to proton ratio in a radioisotope determines the type of decay that occurs.

- When an unstable isotope has too many neutrons relative to the number of protons, it will undergo beta emission.
- There are also instances when an unstable isotope has too few neutrons relative to the number of protons. In that case, the isotope will undergo either electron capture or positron emission.
  - ***Electron capture*** **($^{0}_{-1}e$)** occurs when the nucleus captures an electron, so it is written on the left side of the equation.
  - ***Positron emission*** **($^{0}_{+1}e$)** is when a proton changes to a neutron.
- Atoms with atomic numbers higher than 83 are expected to decay by alpha emission**.**

1. Determine the probable mode of decay for the unstable nuclide in each pair below.

I. $^{14}_{6}C$ and $^{20}_{10}Ne$ II. $^{32}_{16}S$ and $^{242}_{96}Cm$

A. I. electron capture, II. beta emission

B. I. alpha emission, II. beta emission

C. I. beta emission, II. alpha emission

D. I. electron capture, II. alpha emission

14.03

Nuclear Fission and Nuclear Fusion

The nuclei of certain isotopes are ***fissionable***, meaning they can be split into smaller fragments. ***Nuclear fission*** is a process that releases enormous amounts of energy. In a nuclear fission reaction, the fissionable isotope is bombarded with neutrons, causing a chain reaction that creates more neutrons.

- In an uncontrolled nuclear fission reaction, all of the energy is released in a matter of seconds.
- A nuclear reactor releases the energy slowly so that it can be conserved and used safely.
- The control of a nuclear fission reaction can be maintained using two different methods:
    - ***Neutron moderation*** – Slows down neutrons so the reactor fuel can capture them to continue the chain reaction, which helps moderate neutron capture
    - ***Neutron absorption*** – Decreases the number of slow-moving neutrons, which causes the fission to occur slowly

Common elements used in nuclear fission reactions are $^{235}_{92}U$ and $^{239}_{94}Pu$ because they are large enough to break up into smaller particles. A nuclear fission chain reaction has three general steps:

1. ***Initiation.*** The reaction of a single atom is needed to start the chain reaction. For example, $^{235}_{92}U$ is initiated by the capture of a neutron.
2. ***Propagation.*** This part of the chain reaction repeats continuously to yield more products. For example, $^{235}_{92}U$ produces $^{141}_{56}Ba$ + $^{92}_{36}Kr$ + $3^{1}_{0}n$, and with the production of three more neutrons, the chain reaction can continue.
3. ***Termination.*** The chain reaction eventually ends, either when the reactants are used up or, as with certain isotopes (such as $^{235}_{92}U$), when the donation of neutrons stops.

Nuclear fusion occurs when nuclei combine to produce a nucleus of greater mass.

- Solar fusion and hydrogen bombs are examples of nuclear fusion.
- The products of a nuclear fusion reaction are more stable than the reactants, so the process releases a large amount of energy.
- One of the limitations of fusion reactions is that they occur only at very high temperatures.

1. Is this reaction a fission or fusion reaction?

$$^{84}Kr + ^{1}n \rightarrow ^{48}Ca + ^{36}S + ^{1}n$$

2. Which of the following statements is *false*?

A. Nuclear power plants generate heat through nuclear fission reactions.
B. Nuclear fission occurs when a heavy, less stable nuclide is split into lighter, more stable nuclides.
C. Nuclear fusion occurs when lighter, less stable nuclides combine to form a heavier, more stable nuclide.
D. An alpha particle has more penetrating power than a gamma particle.

PERIODIC TABLE OF THE ELEMENTS

	1A	2A	3B	4B	5B	6B	7B	<--- 8B --->			1B	2B	3A	4A	5A	6A	7A	8A
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 H 1.008																	2 He 4.003
2	3 Li 6.941	4 Be 9.012											5 B 10.81	6 C 12.01	7 N 14.01	8 O 16.00	9 F 19.00	10 Ne 20.18
3	11 Na 22.99	12 Mg 24.31											13 Al 26.98	14 Si 28.09	15 P 30.97	16 S 32.07	17 Cl 35.45	18 Ar 39.95
4	19 K 39.10	20 Ca 40.08	21 Sc 44.96	22 Ti 47.88	23 V 50.94	24 Cr 52.00	25 Mn 54.94	26 Fe 55.85	27 Co 58.93	28 Ni 58.69	29 Cu 63.55	30 Zn 65.39	31 Ga 69.72	32 Ge 72.59	33 As 74.92	34 Se 78.96	35 Br 79.90	36 Kr 83.80
5	37 Rb 85.47	38 Sr 87.62	39 Y 88.91	40 Zr 91.22	41 Nb 92.91	42 Mo 95.94	43 Tc (99)	44 Ru 101.1	45 Rh 102.9	46 Pd 106.4	47 Ag 107.9	48 Cd 112.4	49 In 114.8	50 Sn 118.7	51 Sb 121.8	52 Te 127.6	53 I 126.9	54 Xe 131.3
6	55 Cs 132.9	56 Ba 137.3	57 La 138.9	72 Hf 178.5	73 Ta 180.9	74 W 183.9	75 Re 186.2	76 Os 190.2	77 Ir 192.2	78 Pt 195.1	79 Au 197.0	80 Hg 200.6	81 Tl 204.4	82 Pb 207.2	83 Bi 209.0	84 Po (209)	85 At (210)	86 Rn (222)
7	87 Fr (223)	88 Ra 226.0	89 Ac 227.0	104 Rf (261)	105 Ha (262)	106 (263)	107 (262)	108	109									

Lanthanides	58 Ce 140.1	59 Pr 140.9	60 Nd 144.2	61 Pm (145)	62 Sm 150.4	63 Eu 152.0	64 Gd 157.2	65 Tb 158.9	66 Dy 162.5	67 Ho 164.9	68 Er 167.3	69 Tm 168.9	70 Yb 173.0	71 Lu 175.0
Actinides	90 Th 232.0	91 Pa 231.0	92 U 238.0	93 Np 237.0	94 Pu (244)	95 Am (243)	96 Cm (247)	97 Bk (247)	98 Cf (251)	99 Es (252)	100 Fm (257)	101 Md (258)	102 No (259)	103 Lr (260)