Atomic Structures: The Basics

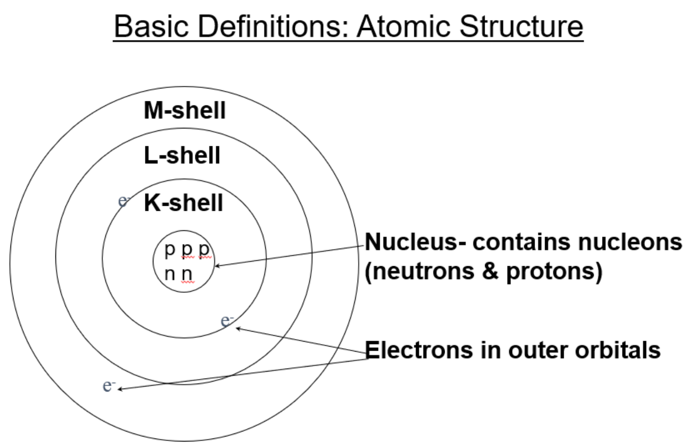
Objectives: Atomic Structure: The Basics

1. To be able to sketch an atom and indicate the location of the nucleus, the shells, and the electronic orbitals
2. To be able to calculate the maximum number of electrons that can occupy a specific shell
3. To identify the symbols for atomic number, atomic mass, and number of neutrons in an atom
4. To explain the difference between the Periodic Table of the Elements and the Chart of the Nuclides
5. To explain the difference between isotopes, isotones, isobars, and isomers and give examples of each.
6. To explain the difference between protons, neutrons, electrons, alpha particles, beta-minus particles, beta-plus particles, X-rays and gamma rays and write the symbols for each.

Atomic Structure: The Basics

1. **Structure of an atom**

   The atom contains a very small nucleus surrounded by shells containing orbitals. These orbitals contain the electrons. Within these shells are orbitals



2. **Orbitals Within Shells**

   Within the K, L, M, N, … shells are orbitals designated s, p, d, and f. These orbitals can hold a maximum of 2, 6, 10, and 14 electrons, respectively. They are arranged in a predictable manner based on their position in the Periodic Table, e.g., the first 36 electrons are filled as follows:

   $1S^22S^22P^63S^23P^64S^23D^{10}4P^6$ etc

   To understand what each of these terms means, let's examine a couple of the terms. $4P^6$ means that, in the 4th shell (the N shell), in the p orbital, there are 6 electrons. $3D^{10}$ means that, in the 3rd shell (the M shell), in the d orbital, there are 10 electrons

3. **Quiz question 1**: What is the formula for the maximum number of electrons that can occupy a particular shell?

   Answer: The maximum number of electrons that can occupy a particular shell is represented by the formula max = $2n^2$ where n = the shell number.

Shell	Formula	Max # of electrons
K	2×1^2	2
L	2×2^2	8
M	2×3^2	18
N	2×4^2	32
O	2×5^2	50

4. Basic Definitions: Atomic Structure

For the nuclide $_{N}X_{Z}^{A}$

Z = # of p^+ in nucleus = # of e^- in outer orbitals.

Z = atomic number

A = number of (protons + neutrons)

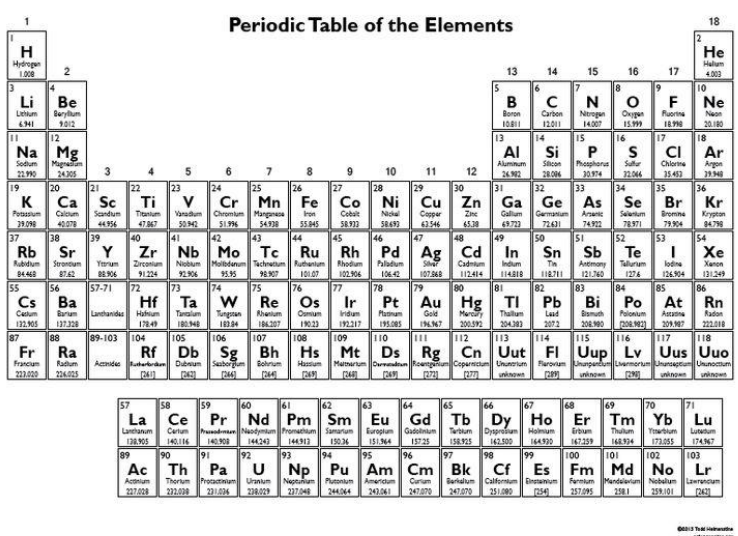
A= atomic mass

N = number of neutrons = $(A - Z)$

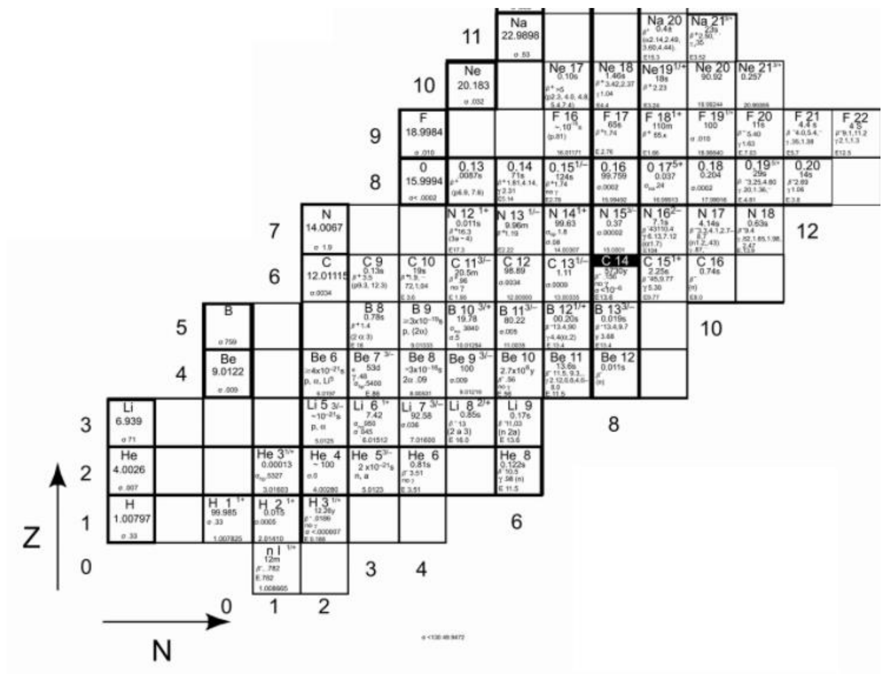
Nucleons= total # of particles in nucleus (p+n)

5. Chart of the Nuclides and Periodic Table of the Elements: What's the Difference?

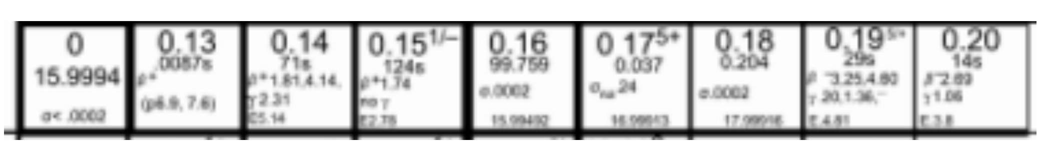
a. The **periodic table** displays all known elements in order of atomic number (number of protons in the nucleus). The pictorial below represents the periodic table through element # 103 (Lawrencium).



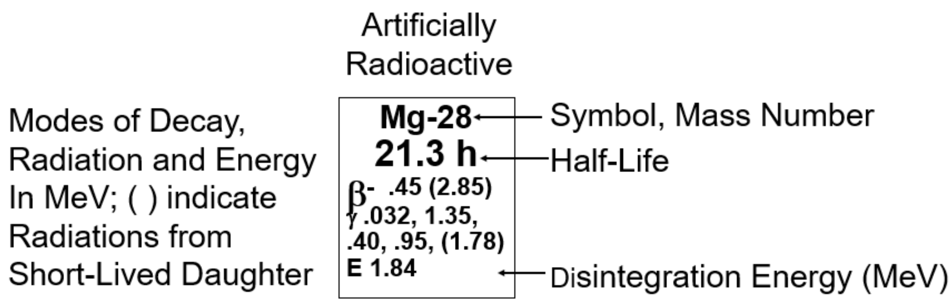
b. The **Chart of the Nuclides** is entirely different and much larger in its entirety. It displays every known isotope (radioactive or not) for every known element in the periodic table. There are approximately 3,000 known nuclides. Displayed below is a small portion of the Chart of the Nuclides. Each of the little boxes in the chart contains a lot of information- the nuclide atomic number and mass; its half-life if radioactive and its % abundance in the universe if stable; the types of emissions and their associated energies (if radioactive) along with the disintegration energy expended in decaying from parent to daughter. The small portion of the chart shown below includes every known nuclide of elements 1-11.



6. If we focus on just the oxygen isotopes taken from the chart above and displayed below, we can see that O-16, O-17, and O-18 are not radioactive and the % abundances of these three oxygen isotopes are listed in the respective boxes. However, for the other 5 isotopes, all of which are radioactive, their half-lives are listed. % abundance is not listed because they do not occur naturally and the value would be 0. The first box shows the molecular weight of Oxygen as 15.9994, which is the weighted average of the molecular weights of the three stable isotopes.



7. There is a lot of information in each box as shown below for Mg-28.



Isotopes, isotones, isobars, and isomers

a. **Isotopes**: nuclides with constant Z number (equal number of protons), but different A and N numbers

examples: Ca_{20}^{40} Ca_{20}^{42} Ca_{20}^{45}

b. **Isotones**: nuclides with constant N number (equal number of neutrons), but different A and Z numbers)

examples: Ar_{18}^{40} K_{19}^{41} Ca_{20}^{42}

c. **Isobars**: nuclides with constant A number (equal number of protons + neutrons), but different Z and N numbers)

examples: Ar_{18}^{40} K_{19}^{40} Ca_{20}^{40}

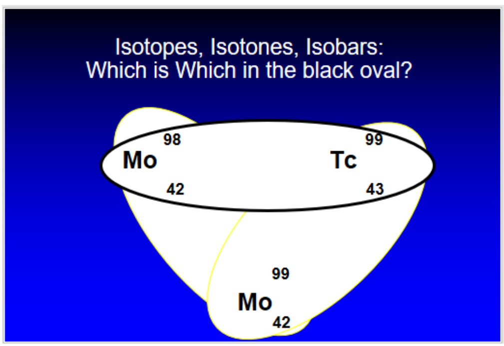
d. **Isomers**: 2 identical atoms, one in an excited nuclear state and the other in a de-excited nuclear state. A, Z, and N numbers are all identical. Isomers are inseparable by chemical or physical means

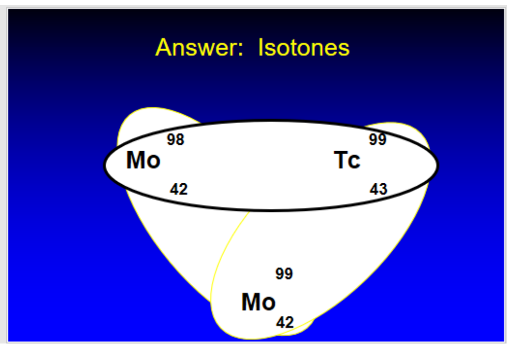
example: Tc_{43}^{99m} and Tc_{43}^{99g}

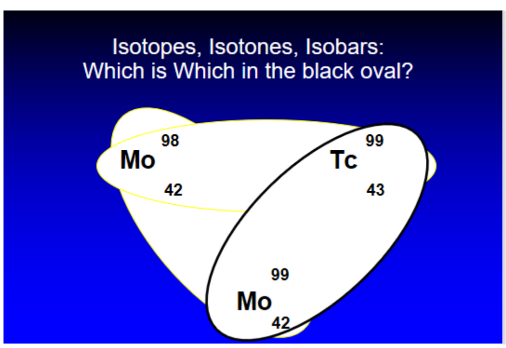
e. What do Isotopes, Isotones, and Isobars have in common? **Each of these has one number constant and two numbers variable**

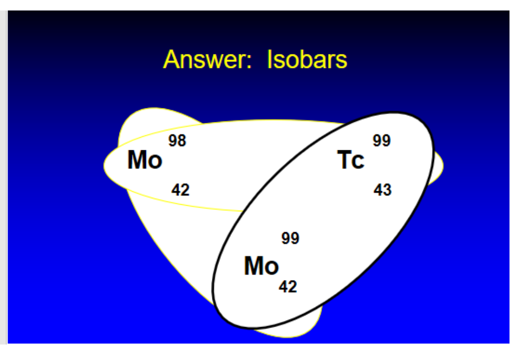
f. The **m** in 99m refers to a metastable state, defined as an excited nuclear state characterized by a *measurable half-life*; "measurable" means $\geq$ 1 μsec. The daughter atom's A, Z, and N numbers are identical to those of the parent atom. Decay is by *isomeric transition* to the ground state.

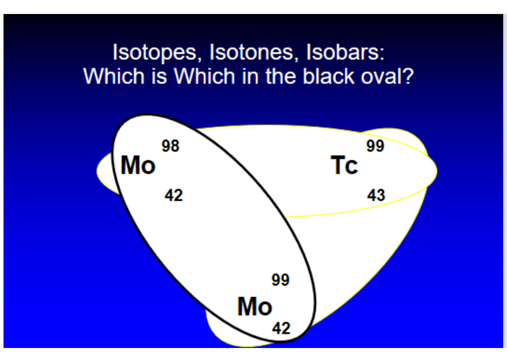
8. Isotopes, Isotones, Isobars: Which is Which?

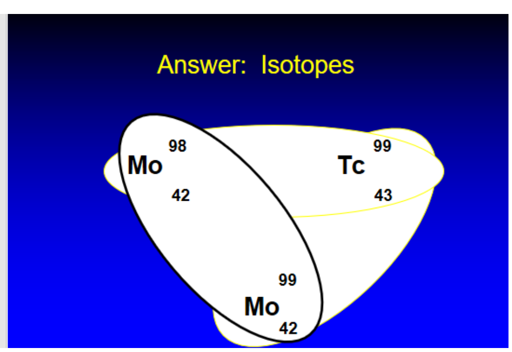












Which of the following lists consists of nuclei that are ISOTONES?

a) I^{131}_{53} Xe^{131}_{54} Te^{131}_{52} Sb^{131}_{51}

b) I^{131}_{53} Xe^{132}_{54} Te^{130}_{52} Sb^{129}_{51}

c) Cs^{129}_{55} Xe^{129}_{54} I^{129}_{53}

d) a and c

Answer: choice b

Which of the following lists consists of nuclei that are ISOBARS?

a) I^{131}_{53} Xe^{131}_{54} Te^{131}_{52} Sb^{131}_{51}

b) I^{131}_{53} Xe^{132}_{54} Te^{130}_{52} Sb^{129}_{51}

c) Cs^{129}_{55} Xe^{129}_{54} I^{129}_{53}

d) a and c

Answer: choice d

Consider Tc^{99m} and Tc^{99g}, a pair of nuclear isomers. TRUE/FALSE: since both atoms are Tc and have the same Z number, they are also isotopes.

Answer: False. Tc^{99m} and Tc^{99g} are nuclear isomers. They can NOT be isotopes, isotones, or isobars because each of those requires one number constant and the other two numbers variable. In this case, all the numbers for each isomer are exactly the same.

9. **Protons, neutrons, electrons, and emitted particles and photons: description and symbols**

   a. **<u>Alpha particle</u>**: An alpha particle is a helium nucleus and may be written He^{4}_{2} or α^{4}_{2}. All helium in our atmosphere results from alpha decay.

b. **Beta minus particle**: identical to an ordinary electron other than its source (the nucleus rather than outer orbitals). Written e^{0}_{-1} or β^{0}_{-1}

c. **Beta plus particle**: antimatter to an ordinary electron and undergoes an annihilation reaction with it. Written e^{0}_{+1} or β^{0}_{+1}

Beta-plus particles, also called positrons, have a very short lifetime in matter- they readily annihilate electrons once they have lost almost all their kinetic energy. The radiation emitted is called *annihilation radiation* and is always 2 photons emitted at a 180^{o} angle with an energy of 511 keV.

d. **Gamma Ray**: Electromagnetic radiation; charge = 0 and mass = 0. Written γ_0^0 Identical to an X-ray other than its source (the nucleus rather than outer orbitals).

e. **X-Ray**: Electromagnetic radiation; charge = 0 and mass = 0. Identical to a γ-ray other than its source (outer orbitals rather than the nucleus). Not written with charge/mass since X-rays are not emitted from nucleus and therefore don't participate in nuclear decay.

f. **Neutron**: Symbol: n_0^1. Found only in nucleus. Neutral charge; mass slightly greater than mass of proton. Never emitted spontaneously.

g. **Proton**: Symbol: H_1^1 or P_1^1. Found only in nucleus. Its positive charge is counter-balanced by an electron in an outer orbital. Never emitted spontaneously. Other isotopes of hydrogen: deuterium (H_1^2) and tritium (H_1^3). Tritium is radioactive with a 12.3 year half-life.

The following section contains practice problems.

10. **Problem**

For $^{99}_{43}Tc$ how many neutrons?
protons?
electrons?
positrons?
freons?
nucleons?
what is the atomic mass?
atomic number?

Answer

Neutrons = 56
Protons = 43
Electrons = 43
Positrons = 0
Freons = 0
Nucleons = 99
atomic mass = 99
atomic number = 43

11. **Problem:** An atomic nucleus contains 39 protons and 50 neutrons. Its mass number (A) is

a) 39
b) 50
c) 11
d) 89

Correct answer is "d". The mass number is determined by addition of the number of protons and neutrons in the nucleus. Collectively they are referred to as nucleons.

12. **Problem:** In standard notation, one of the isotopes of bromine is Br-73. The atomic number is 35. How many neutrons does this nucleus contain?

a) 38
b) 73
c) 35
d) 108

Correct answer is "a". The number of neutrons is determined by subtracting the number of protons from the mass number.

13. **Question:** The fundamental particles of greatest interest in the physics of nuclear medicine are the proton, the neutron, and the electron. Of these

a) the electron is the least massive and has negative charge
b) the proton is the least massive and has negative charge
c) the proton is the least massive and has positive charge
d) the neutron is the most massive and has positive charge

Correct answer is "a". Choice "b" is incorrect- the proton is more massive than any other particle except a neutron and its charge is positive, not negative. "c" is incorrect since protons are not the least massive. "d" is incorrect since neutrons don't have a positive charge.

14. **Question:** A parent nucleus decays by emitting a gamma photon, e.g., Tc-99m decays to Tc-99g. Parent and daughter nuclei are:

a) isotopes
b) isotones
c) isobars
d) isomers
e) combination of 2 or more of the above

Correct answer is "d". All other answers are incorrect since the other "iso" terms require one number to be constant and the other two numbers to be variable. Isomers can never be isotopes, isotones, or isobars.

15. **Question:** In β^- decay, which of the following is emitted?

a) an ordinary electron
b) a positron
c) a positron/electron pair
d) annihilation radiation

Correct answer is "a". In β- decay, an electron is emitted from the nucleus. Other than the source (nucleus rather than outer orbitals), it is indistinguishable from an ordinary electron.

16. **Question:** For an unknown isotope X mark each of the following statements True or False.

a) The Z number represents the number of protons
b) The Z number represents the number of electrons
c) The neutrons are represented by (Z-A)
d) Electrons in outer orbitals are electrically balanced by positrons in the nucleus
e) The mass number A = (2Z + N)

Correct answers are "T, T, F, F, F". Statement "c" is false- neutrons are represented by (A-Z), not (Z-A); Statement "d" is false- electrons are balanced by protons, not positrons; Statement "e" is false- mass number A = Z + N.

17. **Question:** Gamma rays are <u>most</u> similar to which <u>one</u> of the following

a) X-rays
b) high speed electrons
c) infrared radiation
d) sound waves
e) laser beams

Correct answer is "a". Gamma rays and X-rays of the same energy have identical interactions in matter. The primary difference is their source: gammas are emitted from the nucleus; X-rays, from the outer orbitals.

18. **Question:** The ^{99m}Tc nucleus is a metastable state of Tc. This means that

a) It will decay to ^{99g}Tc by emitting gamma radiation, immediately after it is formed.
b) It will decay by emitting an alpha particle immediately after it is formed
c) It will decay by emitting a gamma photon some measurable time after it is formed.
d) It will not undergo radioactive decay.

Correct answer is "c". The definition of a metastable state is an excited state with a measurable half-life. As a rule of thumb, half-lives > 1 μsec are considered measurable.

19. **Question:** The decay of Tc-99m to Tc-99g is an example of:

a) internal conversion
b) neutrino production
c) isomeric transition
d) photoelectric effect
e) none of the above

Correct answer is "c". Decay of Tc-99m to Tc-99g (ground state) is a perfect example of isomeric transition. An excited Tc-99m atom de-excites itself and emits a gamma ray. The A, Z, and N numbers remain unchanged; only the energy level has been reduced. The ground state has a different half-life (2.2×10^5 years) than the metastable state (6 hr).