

## Atomic Structures: The Basics

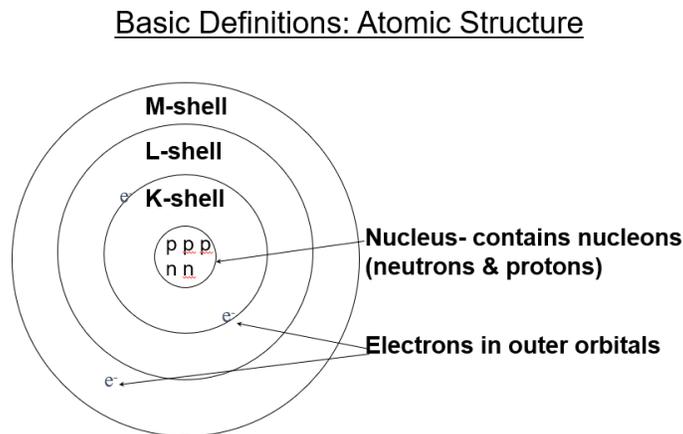
### **Objectives: Atomic Structure: The Basics**

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:



To understand what each of these terms means, let's examine a couple of the terms.  $4P^6$  means that, in the 4<sup>th</sup> shell (the N shell), in the p orbital, there are 6 electrons.  $3D^{10}$  means that, in the 3<sup>rd</sup> 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  $\text{max} = 2n^2$  where  $n$  = the shell number.

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

#### 4. Basic Definitions: Atomic Structure

A  
For the nuclide  ${}_N X_Z$

$Z = \# \text{ of } p^+ \text{ in nucleus} = \# \text{ of } e^- \text{ in outer orbitals.}$

$Z = \text{atomic number}$

$A = \text{number of (protons + neutrons)}$

$A = \text{atomic mass}$

$N = \text{number of neutrons} = (A - Z)$

$\text{Nucleons} = \text{total } \# \text{ of particles in nucleus (p+n)}$

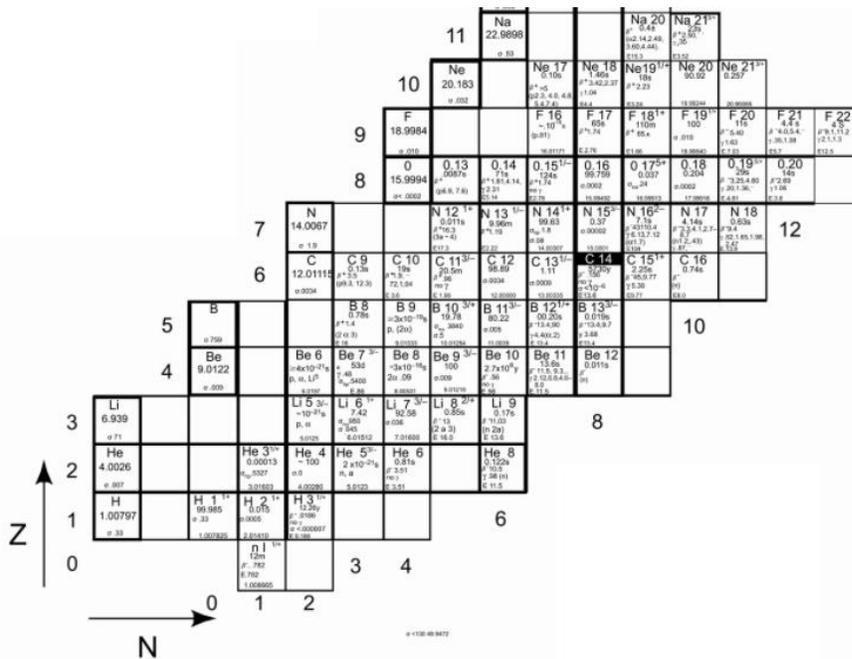
#### 5. Chart of the Nuclides and Periodic Table of the Elements: What's the Difference?

- 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).

**Periodic Table of the Elements**

1 H Hydrogen 1.008																	2 He Helium 4.003
3 Li Lithium 6.941	4 Be Beryllium 9.012											5 B Boron 10.811	6 C Carbon 12.011	7 N Nitrogen 14.007	8 O Oxygen 15.999	9 F Fluorine 18.998	10 Ne Neon 20.180
11 Na Sodium 22.990	12 Mg Magnesium 24.305											13 Al Aluminum 26.982	14 Si Silicon 28.086	15 P Phosphorus 30.974	16 S Sulfur 32.064	17 Cl Chlorine 35.453	18 Ar Argon 39.948
19 K Potassium 39.098	20 Ca Calcium 40.078	21 Sc Scandium 44.956	22 Ti Titanium 47.887	23 V Vanadium 50.942	24 Cr Chromium 51.996	25 Mn Manganese 54.938	26 Fe Iron 55.845	27 Co Cobalt 58.933	28 Ni Nickel 58.693	29 Cu Copper 63.546	30 Zn Zinc 65.38	31 Ga Gallium 69.723	32 Ge Germanium 72.631	33 As Arsenic 74.922	34 Se Selenium 78.971	35 Br Bromine 79.904	36 Kr Krypton 84.798
37 Rb Rubidium 84.464	38 Sr Strontium 87.62	39 Y Yttrium 88.906	40 Zr Zirconium 91.224	41 Nb Niobium 92.906	42 Mo Molybdenum 95.95	43 Tc Technetium 98.907	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.905	46 Pd Palladium 106.42	47 Ag Silver 107.868	48 Cd Cadmium 112.414	49 In Indium 114.818	50 Sn Tin 118.710	51 Sb Antimony 121.760	52 Te Tellurium 127.6	53 I Iodine 126.904	54 Xe Xenon 131.29
55 Cs Cesium 132.905	56 Ba Barium 137.328	57-71 La-Lu Lanthanides	72 Hf Hafnium 178.49	73 Ta Tantalum 180.948	74 W Tungsten 183.84	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.222	78 Pt Platinum 195.085	79 Au Gold 196.967	80 Hg Mercury 200.592	81 Tl Thallium 204.383	82 Pb Lead 207.2	83 Bi Bismuth 208.980	84 Po Polonium [209]	85 At Astatine [210]	86 Rn Radon [222]
87 Fr Francium 223.028	88 Ra Radium 226.025	89-103 Ac-Lr Actinides	104 Rf Rutherfordium [261]	105 Db Dubnium [262]	106 Sg Seaborgium [263]	107 Bh Bohrium [264]	108 Hs Hassium [265]	109 Mt Meitnerium [266]	110 Ds Darmstadtium [267]	111 Rg Roentgenium [268]	112 Cn Copernicium [269]	113 Uut Ununtrium [270]	114 Fl Flerovium [271]	115 Uup Ununpentium [272]	116 Lv Livermorium [273]	117 Uus Ununseptium [274]	118 Uuo Ununoctium [275]
57 La Lanthanum 138.905	58 Ce Cerium 140.116	59 Pr Praseodymium 140.908	60 Nd Neodymium 144.242	61 Pm Promethium [145]	62 Sm Samarium 150.36	63 Eu Europium 151.964	64 Gd Gadolinium 157.25	65 Tb Terbium 158.925	66 Dy Dysprosium 162.502	67 Ho Holmium 164.930	68 Er Erbium 167.259	69 Tm Thulium 168.934	70 Yb Ytterbium 173.054	71 Lu Lutetium 174.967			
89 Ac Actinium 227.028	90 Th Thorium 232.038	91 Pa Protactinium 231.036	92 U Uranium 238.029	93 Np Neptunium 237.048	94 Pu Plutonium 244.064	95 Am Americium 243.061	96 Cm Curium 247.070	97 Bk Berkelium 247.070	98 Cf Californium 251.080	99 Es Einsteinium 252.083	100 Fm Fermium 257.095	101 Md Mendelevium 258.1	102 No Nobelium 259.101	103 Lr Lawrencium [260]			

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.

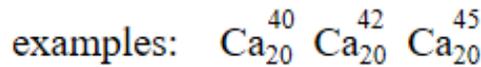
0 15.9994 α<.0002	0.13 0.037% β <sup>+</sup> (p4.8, 7.6)	0.14 71s β <sup>+</sup> 1.814.14, γ2.31 25.14	0.15 <sup>1/-</sup> 124s β <sup>+</sup> 1.74 no γ 22.78	0.16 99.759 α0.0002 15.999492	0.17 <sup>5+</sup> 0.037 α <sub>ns</sub> 24 16.99913	0.18 0.204 α0.0002 17.99916	0.19 <sup>5+</sup> 29s β <sup>-</sup> 3.25.4.80 γ20.1.36, 5.41	0.20 14s β <sup>-</sup> 2.89 γ1.06 17.99916
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7. There is a lot of information in each box as shown below for Mg-28.

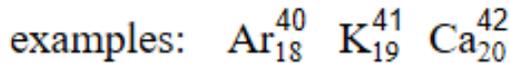
	Artificially Radioactive	
Modes of Decay, Radiation and Energy In MeV; ( ) indicate Radiations from Short-Lived Daughter	<b>Mg-28</b> <b>21.3 h</b> $\beta^-$ .45 (2.85) $\gamma$ .032, 1.35, .40, .95, (1.78) <b>E 1.84</b>	← Symbol, Mass Number ← Half-Life ← Disintegration Energy (MeV)

**Isotopes, isotones, isobars, and isomers**

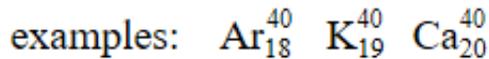
a. **Isotopes:** nuclides with constant Z number (equal number of protons), but different A and N numbers



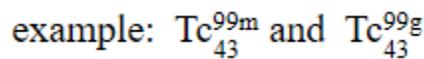
b. **Isotones:** nuclides with constant N number (equal number of neutrons), but different A and Z numbers)



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



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



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  $\geq 1 \mu\text{sec}$ . 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?

Isotopes, Isotones, Isobars:  
Which is Which in the black oval?

Answer: Isotones

Isotopes, Isotones, Isobars:  
Which is Which in the black oval?

Answer: Isobars

Isotopes, Isotones, Isobars:  
Which is Which in the black oval?

Answer: Isotopes

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

- a)  $\text{I}^{131}_{53}$   $\text{Xe}^{131}_{54}$   $\text{Te}^{131}_{52}$   $\text{Sb}^{131}_{51}$
- b)  $\text{I}^{131}_{53}$   $\text{Xe}^{132}_{54}$   $\text{Te}^{130}_{52}$   $\text{Sb}^{129}_{51}$
- c)  $\text{Cs}^{129}_{55}$   $\text{Xe}^{129}_{54}$   $\text{I}^{129}_{53}$
- d) a and c

**Answer: choice b**

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

- a)  $\text{I}^{131}_{53}$   $\text{Xe}^{131}_{54}$   $\text{Te}^{131}_{52}$   $\text{Sb}^{131}_{51}$
- b)  $\text{I}^{131}_{53}$   $\text{Xe}^{132}_{54}$   $\text{Te}^{130}_{52}$   $\text{Sb}^{129}_{51}$
- c)  $\text{Cs}^{129}_{55}$   $\text{Xe}^{129}_{54}$   $\text{I}^{129}_{53}$
- d) a and c

**Answer: choice d**

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

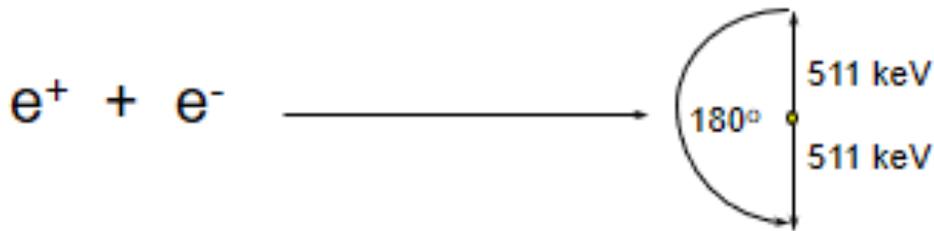
**Answer: False.**  $\text{Tc}^{99\text{m}}$  and  $\text{Tc}^{99\text{g}}$  are nuclear isomers. They can NOT be isotopes, isotones, or isobars because each of those requires one number constant and the other two numbers variable. In this case, all the numbers for each isomer are exactly the same.

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

- a. **Alpha particle:** An alpha particle is a helium nucleus and may be written  $\text{He}^4_2$  or  $\alpha^4_2$ .  
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  $e^{-0}$  or  $\beta^{-0}$
- c. **Beta plus particle**: antimatter to an ordinary electron and undergoes an annihilation reaction with it. Written  $e^{+0}$  or  $\beta^{+0}$

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  $180^\circ$  angle with an energy of 511 keV.



- d. **Gamma Ray**: Electromagnetic radiation; charge = 0 and mass = 0. Written  $\gamma^0$ . 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  $\gamma$ -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  ${}_{43}^{99}\text{Tc}$  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  $\beta^-$  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  $\beta^-$  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 most similar to which one 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  $^{99m}\text{Tc}$  nucleus is a metastable state of Tc. This means that

- a) It will decay to  $^{99g}\text{Tc}$  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  $> 1 \mu\text{sec}$  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 ( $2.2 \times 10^5$  years) than the metastable state (6 hr).