**ATOMIC PHYSICS**

Atoms are mostly empty space.

Atoms have a diffuse cloud of electrons that surround a dense nucleus.

An atom's nucleus contains protons and neutrons.

A neutron and a proton have about the same mass.

The mass of an electron is over 1800 times smaller than the mass of a proton.

Protons have positive charge. Neutrons have no charge. Electrons have negative charge.

There are 117 known types of atoms, one for each known element.

The Periodic Table is an ordered listing of all of the known elements.

atomic mass unit = (mass of a Carbon-12 atom)/12 = amu

atomic number = number of protons

atomic mass number = number of protons + number of neutrons.

atomic mass = (mass of nucleus) / (1 amu) (also called "atomic weight")

Electrons surround the nucleus in shells of various radii (Bohr Model).

Each shell is assigned a "principal quantum number" *n* and a letter:

| quantum number (*n*) | letter |
|---|---|
| 1 | K |
| 2 | L |
| 3 | M |
| 4 | N |
| 5 | O |
| 6 | P |

Each shell can hold $2n^2$ electrons.

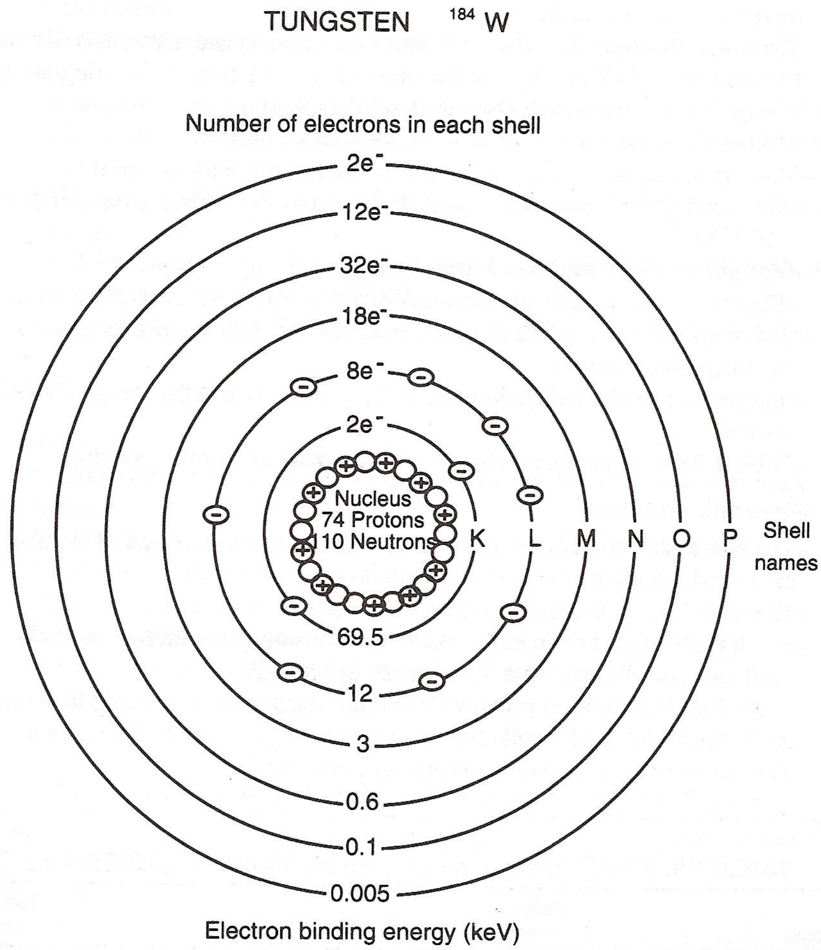


**FIG. 1.** Bohr model of the atom showing tungsten with a total of 74 protons, 74 electrons, and 110 neutrons. The electron binding energy decreases rapidly with electron distance from the nucleus.

Atomic electrons are held in place by electrostatic force, which decreases rapidly with distance from the nucleus.

**Electron binding energy** is the energy (work) required to remove an electron from an atom. The binding energy of outer-shell electrons is small (several eV).

The binding energy of inner-shell electrons is large (thousands of eV).

K-shell binding energies increase with atomic number.

A particle can knock out inner-shell electrons only if their energy is greater than the electron binding energy.

example: For Tungsten: (K-shell binding energy) = 69.5 keV).
So an electron with kinetic energy greater than this is required to knock a Tungsten K-shell electron out of the atom

Electrons jumping from an outer shell to an inner shell emit the energy difference between the shells as electromagnetic radiation.

Four quantum numbers required for the complete specification of the state of each electron

| label | name | meaning | values | use |
|---|---|---|---|---|
| $n$ | principal | determines electron's energy | $1, 2, \ldots, \infty$ | $E_n = \frac{E_1}{n^2}$ |
| $l$ | angular momentum | determines electron's orbital angular momentum | $0, \ldots, n - 1$ | $L = \sqrt{l(l+1)}\hbar$ |
| $m_l$ | magnetic | determines z-component of electron's orbital angular momentum | $-l, \ldots, l$ | $L_z = m_l \hbar$ |
| $s$ | spin | determines z-component of electron's spin angular momentum | $\pm \frac{1}{2}$ | $s_z = s\hbar$ |

$\hbar = \frac{h}{2\pi}$, $E_1 = -13.6$ electron Volts (for Hydrogen)

## NUCLEAR PHYSICS

**Nuclear Physics** – the study of the atomic nucleus.

**nuclear constituents** ---Nuclei are composed of protons and neutrons.

**nucleon** -- The collective name for protons and neutrons

**nuclide** -- a nucleus that exists in nature or can be created artificially.

example: A Carbon-14 nucleus is a nuclide, because it exist in nature.

A Carbon-92 nucleus is not a nuclide, because it does not exist in nature and cannot be manufactured.

**isotopes** – nuclides that have same at atomic number.

**isobars** -- nuclides that have the same mass number

**isotones** – nuclides that have the same number of neutrons

**isomer** – an excited state of a nuclide

**<u>Nuclear Stability</u>**

the tendency of a nucleus *not* to decay

Low-mass nuclides with equal numbers of protons and neutrons are stable

High-mass nuclides with more neutrons than protons are stable

Very-high-mass nuclides (Z >82) are unstable

**radionuclide** – an unstable nuclide

**processes of nuclear decay**

**alpha decay** – nuclide emits and alpha particle

**beta decay** – nuclide emits a proton, electron and an anti-neutrino

**gamma "decay"** – nuclide emits a gamma ray photon

## Radioactivity

**radioactive decay** – the transformation of unstable nuclides to stable nuclides via one or more of the decay processes

**half-life** -- the time required for ½ of a sample of radioactive material to decay

**activity** -- the number of decay events per unit time

**Becquerel** -- a unit of radioactive decay = 1 decay event per second

**Curie** – an unit of radioactive decay = $3.7 \times 10^{10}$ Becquerel

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The equation that governs radioactive decay:

$$N = N_0 2^{-t/t_{1/2}}$$

$N$ = the number of nuclei that have yet to decayed
$N_0$ = the initial number of nuclei (that have yet to decay at time $t = 0$)
$t_{1/2}$ = half life
$t$ = elapsed time

Example

**Q.** The half life of Iodine-131 is 8 days. A patient is injected with 2 ml of Iodine-131. How much Iodine 131 remains in this patient after 8 days, 16 days, and 32 days?

**A.** 8 days is 1 half life. So ½ is left, i.e. 1 ml.
16 days is 2 half lives. So ½ x ½ is left, i.e (2 ml) x (1/4) = 0.5 ml.
32 days is 4 half lives. So ½ x ½ x ½ x ½ is left, i.e. (2 ml) x (1/16) = 0.125 ml

**Alpha Decay**

$${}^{A}_{Z}X \rightarrow {}^{A-4}_{Z-2}Y + {}^{4}_{2}He$$

superscript is mass number (number of protons + neutrons)
subscript is atomic number (number of protons)

$X$ is the parent nucleus
$Y$ is the daughter nucleus
$He$ is a nucleus of Helium, i.e. an alpha particle

In other words, the parent decays into the daughter + an alpha particle.

Example:

$^{238}_{92}U \rightarrow ^{234}_{90}Th + ^{4}_{2}He$ half-life = 4.47 x$10^9$ years

$^{226}_{88}Ra \rightarrow ^{222}_{86}Rn + ^{4}_{2}He$ half-life = 1.6 x $10^3$ years

$^{222}_{86}Rn \rightarrow ^{218}_{84}Po + ^{4}_{2}He$ half-life = 3.82 days

$^{218}_{84}Po \rightarrow ^{214}_{82}Pb + ^{4}_{2}He$ half-life = 3.10 minutes

(radium → radon → polonium → lead)

**Beta Decay**

$$^{A}_{Z}X \rightarrow ^{A}_{Z+1}Y + e^{-} + \overline{\nu}$$

$$^{A}_{Z}X \rightarrow ^{A}_{Z-1}Y + e^{+} + \nu$$

$e^-$ is an electron

$e^+$ is a positron (a particle identical to an electron except that it's positively charged)

$\nu$ and $\overline{\nu}$ are extremely light particles called the neutrino and antineutrino respectively.

**Gamma "Decay"**

$$^{A}_{Z}X^{*} \rightarrow ^{A}_{Z}X + \gamma$$

$\gamma$ is gamma ray (a very high energy photon)

$X^*$ denotes a nuclide of element *X* that is in a higher-than-normal energy state. [$X^*$ is an isomer of $X$.]

"Decay" is in quotes, because $X$ does not decay into a nucleus of another element in this process.

**Electron Capture**

$${}_{Z}^{A}X + e^{-} \rightarrow {}_{Z-1}^{A}Y + \nu$$

Proton-rich nucleus captures an inner electron

Proton turns into neutron

$\nu$ is a neutrino

**Radiation Exposure Breakdown for the Typical American**

| Radiation Source | Contribution to Total Exposure (%) | Natural? |
| --- | --- | --- |
| Radon | 55 | Y |
| Internal | 11 | Y |
| Medical X-Rays | 11 | N |
| Terrestrial | 8 | Y |
| Cosmic | 8 | Y |
| Nuclear medicine | 4 | N |
| Consumer products | 3 | N |
| Misc | 1 | N |

Natural sources = 82%
Greatest source: Radon
Most preventable source: Radon

## Nuclear Reactions

Result from collision between nuclei or nuclear particles with other nuclei or other nuclear particles.

Examples

Collision between Helium and Nitrogen nuclei

$${}_{2}^{4}He + {}_{7}^{14}N \rightarrow {}_{8}^{17}O + {}_{1}^{1}H$$

Collision of a neutron with a U-235 nucleus

$${}_{0}^{1}n + {}_{92}^{235}U \rightarrow {}_{36}^{94}Kr + {}_{56}^{139}Ba + 3\,{}_{0}^{1}n + \gamma$$

Equations must balance – the sum of the mass numbers on the right = sum of the mass number on the left. Same for atomic number.

Example. Check the example of a neutron colliding with a U-235 nucleus above.

Left side mass number = 1 + 235 = 236
Right side mass number = 94 + 139 + 3 x 1 + 0 = 236

Left side atomic number = 0 + 92 = 92
Right side atomic number = 36 + 56 + 2 x 0 + 0 = 92

## Nuclear Fission

A fast-moving neutron collides with a large (Z >= 92) nucleus, causing it to

-- split into two smaller nuclei

-- release gamma ray photons

-- release fast moving neutrons

If at least 2 fast neutrons are released, nuclear fission results in a chain reaction.

An example: $^{1}_{0}n + ^{235}_{92}U \rightarrow ^{94}_{36}Kr + ^{139}_{56}Ba + 3^{1}_{0}n + \gamma$

**Chain reaction** – a fission reaction in which the neutrons created by the first splitting of a nucleus go on two split 2 more nuclei that create neutrons that go on to spit 4 more
A controlled chain reaction is occurs in a **nuclear reactor.**

An uncontrolled chain reaction occurs in an **atomic bomb.**

## Nuclear Fusion

The fusion of two or more nuclei or nuclear particles.

Release energy, because the resultant fused nucleus has lower energy than the free nuclei or nuclear particles that collided.

Powers the sun and other stars.

No fusion reactors yet, only fusion bombs.

Difficult to cause to occur. Requires many collision attempts for each fusion event, i.e. requires very high temperatures (as in the fission bomb that ignites a fusion bomb or in the sun)

Example: A proton and a deuteron (an isotope of hydrogen) collide to form a helium nuclide while releasing a gamma ray photon.

$$^{1}_{1}H + ^{2}_{1}H \rightarrow ^{3}_{2}He + \gamma$$

**Reaction Energy (Q)**

**= (**Rest Energy of Reactants) - (Rest Energy of Products)

= [(Sum of Rest Masses of Reactant) – (Sum of Rest Masses of Products)] x $c^2$

Q > 0 ➔ Exothermic reaction (energy released)
Q < 0 ➔ Endothermic reaction (energy absorbed)

Mass Deficit = (Sum of Rest Masses of Reactant) – (Sum of Rest Masses of Products)

Mass Defect = (Sum of Rest Masses of Reactant) – (Rest Mass of Product)
*for a hypothetical reaction in which the reactants are the nucleons that comprise a particular nucleus and the sole product is the nucleus itself*

Nuclear Binding Energy = (Mass Defect) X $c^2$