# CHEM103
# General Chemistry

## Chapter 7: Periodic Properties of the Elements

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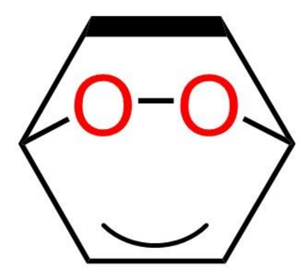


# Assignment 6

## Homework 6

Due date: 24th Oct. (Wed)

# Review on Chapter 6

Arrangement of Electrons of an Atom in Atomic Orbitals

**Light**: Quantized Energy, Photoelectric Effect, Photon, Wave-Particle Duality, Bohr Model, Matter Wave, Uncertainty Principle

**Quantum Mechanics**: Schrödinger (Wave) Equation, Wave Function, Electron Density

**Electrons & Orbitals**: Quantum Numbers, Electron Shell, Spin, Pauli Exclusion Principle, Hund's Rule, Electron Configurations

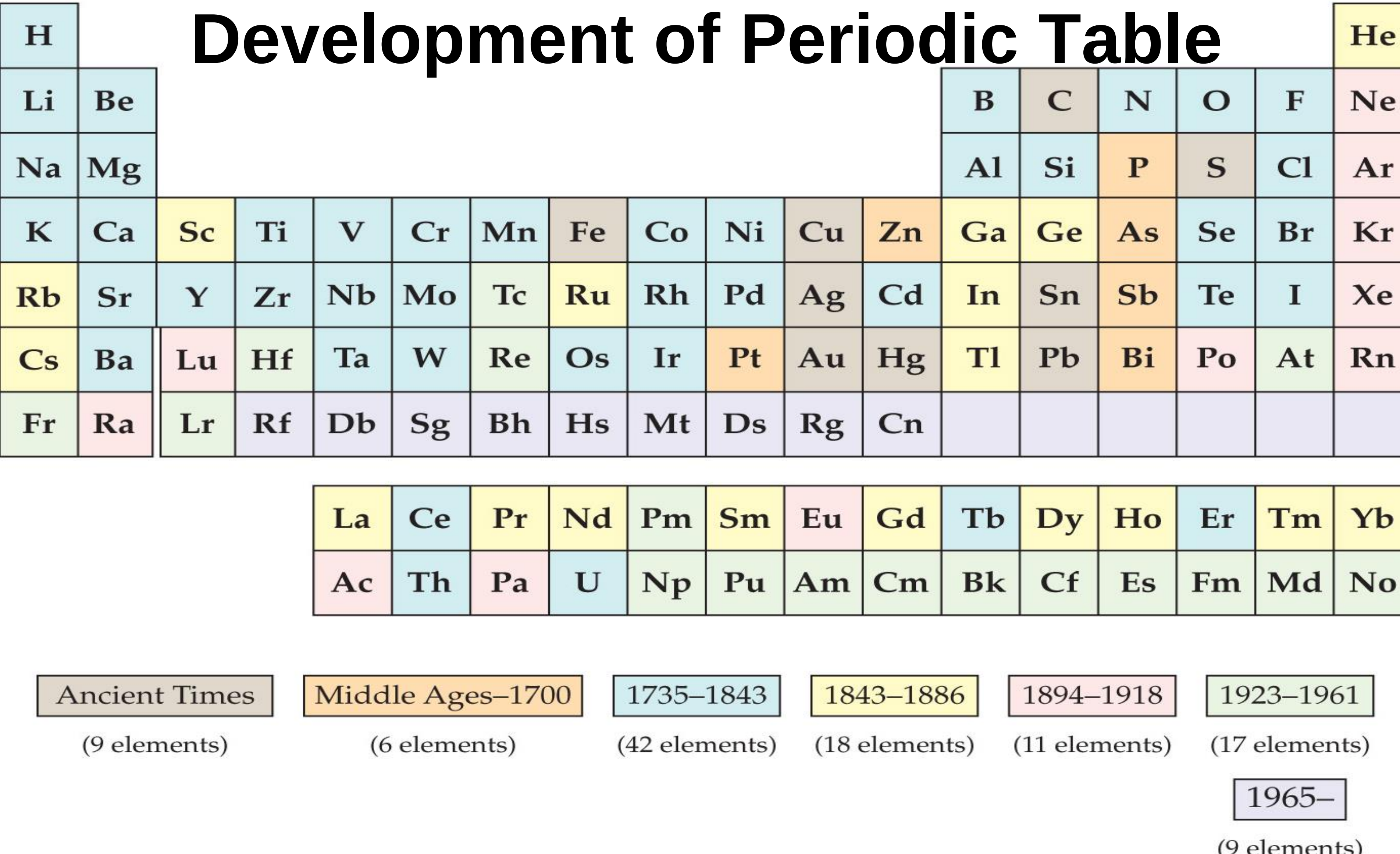
# Outline of Chapter 7

**Development/History of Periodic Table**

**Periodic Trends**:
Effective Nuclear Charge: Shielding
Sizes of Atoms & Ions: (non-) bonding atomic radius;
Ionization Energy
Electron Affinity

**Properties of Metal, Nonmetals, and Metalloids**

# Development of Periodic Table




Dmitrij Ivanovič Mendeleev (Russian chemist and inventor) and Lothar Meyer (German chemist) independently came to the same conclusion about how elements should be grouped.

# Development of Periodic Table

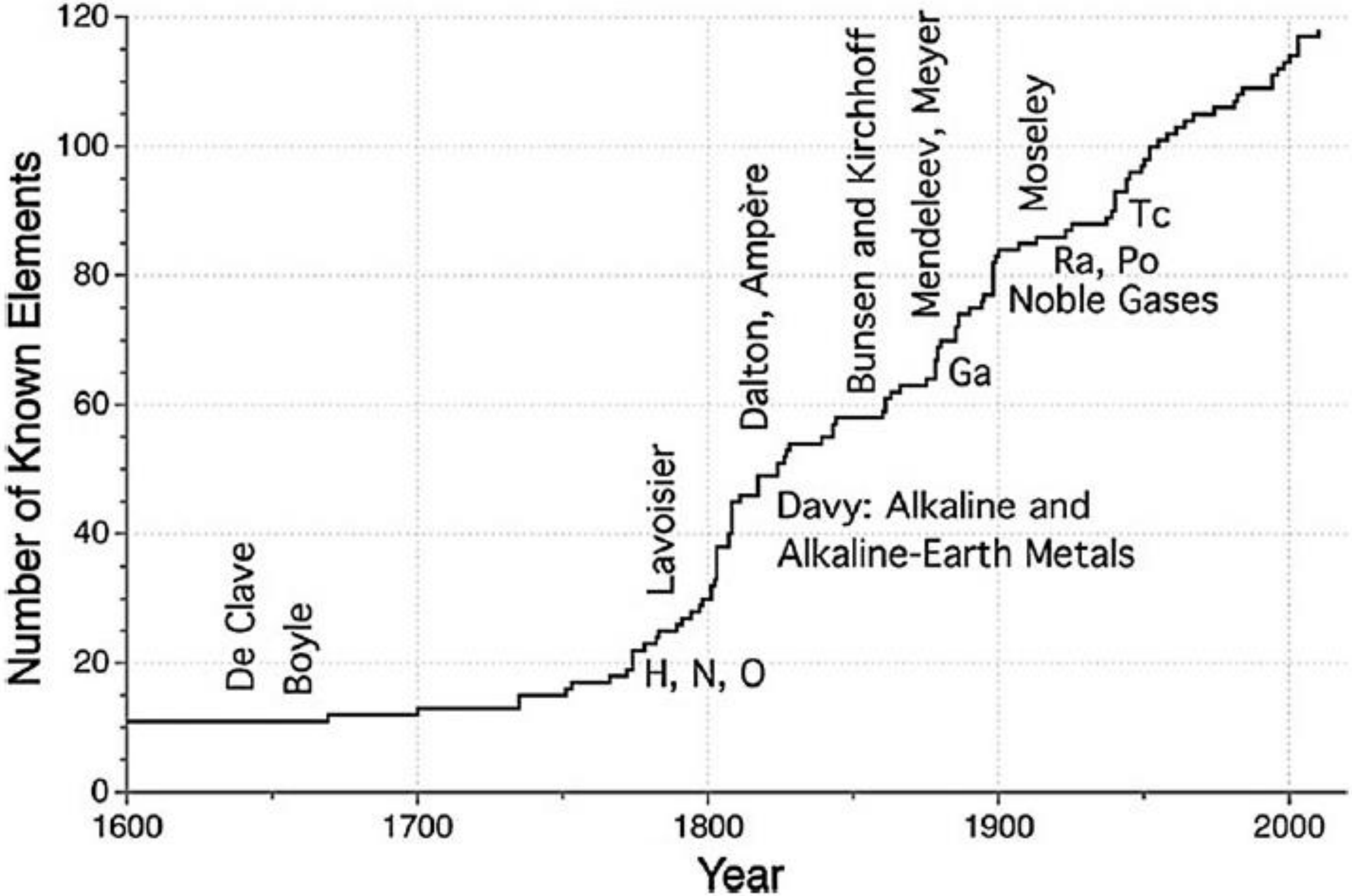



*Figure 1.* A plot of the number of elements discovered per year. Adapted with permission from ref. [4].



*Angew. Chem. Int. Ed.* **2019**, *58*, 13194


Students design tiles

# 2019 International Year of the Periodic Table

## Timeline of Elements

| | |
|---|---|
| BCE | Cu, Pb, Ag, Au, Fe, C, Sn, S, Hg, Zn |
| CE to 1734 | As, Sb, P, Bi |
| 1735–1744 | Co |
| 1745–1754 | Ni, Pt |
| 1755–1764 | Mg |
| 1765–1774 | H, O, N, Ba, Cl, Mn |
| 1775–1784 | Mo, W, Te |
| 1785–1794 | Sr, Zr, U, Ti, Y |
| 1795–1804 | Cr, Be, V, Nb, Ta, Pd, Ce, Os, Ir, Rh |
| 1805–1814 | Na, K, B, Ca, I |
| 1815–1824 | Li, Se, Cd, Si |
| 1825–1834 | Al, Br, Th |
| 1835–1844 | La, Tb, Er, Ru |
| 1845–1854 | |
| 1855–1864 | Cs, Rb, Tl, In |
| 1865–1874 | He, Ge, Tm |
| 1875–1884 | Ga, Ho, Yb, Sc, Sm, Gd |
| 1885–1894 | Pr, Nd, Dy, Ar, F |
| 1895–1904 | Eu, Ne, Kr, Xe, Po, Ra, Rn, Ac |
| 1905–1914 | Lu, Pa |
| 1915–1924 | Hf |
| 1925–1934 | Re |
| 1935–1944 | Tc, Fr, At, Np, Pu, Am, Cm |
| 1945–1954 | Pm, Bk, Cf, Es, Fm |
| 1955–1964 | Md, No, Rf |
| 1965–1974 | Db, Sg, Lr |
| 1975–1984 | Bh, Mt, Hs |
| 1985–1994 | Ds, Rg |
| 1995–2004 | Fl, Lv, Nh, Cn |
| 2005–2019 | Og, Mc, Ts |

**Celebrating the discovery of elements**

A collaborative University of Waterloo project

uwaterloo.ca/chemistry/timeline-of-elements

UNIVERSITY OF WATERLOO
FACULTY OF SCIENCE

# Mendeleev's 1871 Periodic Table

| Reihen | Gruppo I. — $R^2O$ | Gruppo II. — $RO$ | Gruppo III. — $R^2O^3$ | Gruppo IV. $RH^4$ $RO^2$ | Gruppo V. $RH^3$ $R^2O^5$ | Gruppo VI. $RH^2$ $RO^3$ | Gruppo VII. $RH$ $R^2O^7$ | Gruppo VIII. — $RO^4$ |
|---|---|---|---|---|---|---|---|---|
| 1 | H=1 | | | | | | | |
| 2 | Li=7 | Be=9,4 | B=11 | C=12 | N=14 | O=16 | F=19 | |
| 3 | Na=23 | Mg=24 | Al=27,3 | Si=28 | P=31 | S=32 | Cl=35,5 | |
| 4 | K=39 | Ca=40 | —=44 | Ti=48 | V=51 | Cr=52 | Mn=55 | Fe=56, Co=59, Ni=59, Cu=63. |
| 5 | (Cu=63) | Zn=65 | —=68 | —=72 | As=75 | Se=78 | Br=80 | |
| 6 | Rb=85 | Sr=87 | ?Yt=88 | Zr=90 | Nb=94 | Mo=96 | —=100 | Ru=104, Rh=104, Pd=106, Ag=108. |
| 7 | (Ag=108) | Cd=112 | In=113 | Sn=118 | Sb=122 | Te=125 | J=127 | |
| 8 | Cs=133 | Ba=137 | ?Di=138 | ?Ce=140 | — | — | — | — — — — |
| 9 | (—) | — | — | — | — | — | — | |
| 10 | — | — | ?Er=178 | ?La=180 | Ta=182 | W=184 | — | Os=195, Ir=197, Pt=198, Au=199. |
| 11 | (Au=199) | Hg=200 | Tl=204 | Pb=207 | Bi=208 | — | — | |
| 12 | — | — | — | Th=231 | — | U=240 | — | — — — — |

On 6 March 1869, Mendeleev made a formal presentation to the entitled "*The Dependence between the Properties of the Atomic Weights of the Elements*", which described elements according to both atomic weight and valence.

## able 7.1 Comparison of the Properties of Eka-Silicon Predicted by Mendeleev ith the Observed Properties of Germanium

| Property | Mendeleev's Predictions for Eka-Silicon (made in 1871) | Observed Properties of Ge (discovered in 1886) |
|---|---|---|
| Atomic weight | 72 | 72.59 |
| Density ($g/cm^3$) | 5.5 | 5.35 |
| Specific heat (J/g-K) | 0.305 | 0.309 |
| Melting point (°C) | High | 947 |
| Color | Dark gray | Grayish white |
| Formula of oxide | $XO_2$ | $GeO_2$ |
| Density of oxide ($g/cm^3$) | 4.7 | 4.70 |
| Formula of chloride | $XCl_4$ | $GeCl_4$ |
| Boiling point of chloride (°C) | A little under 100 | 84 |

Mendeleev predicted the discovery of germanium (which he called eka-silicon) as an element with an atomic weight between that of zinc & arsenic, but with chemical properties similar to those of silicon.

# Extra Info:

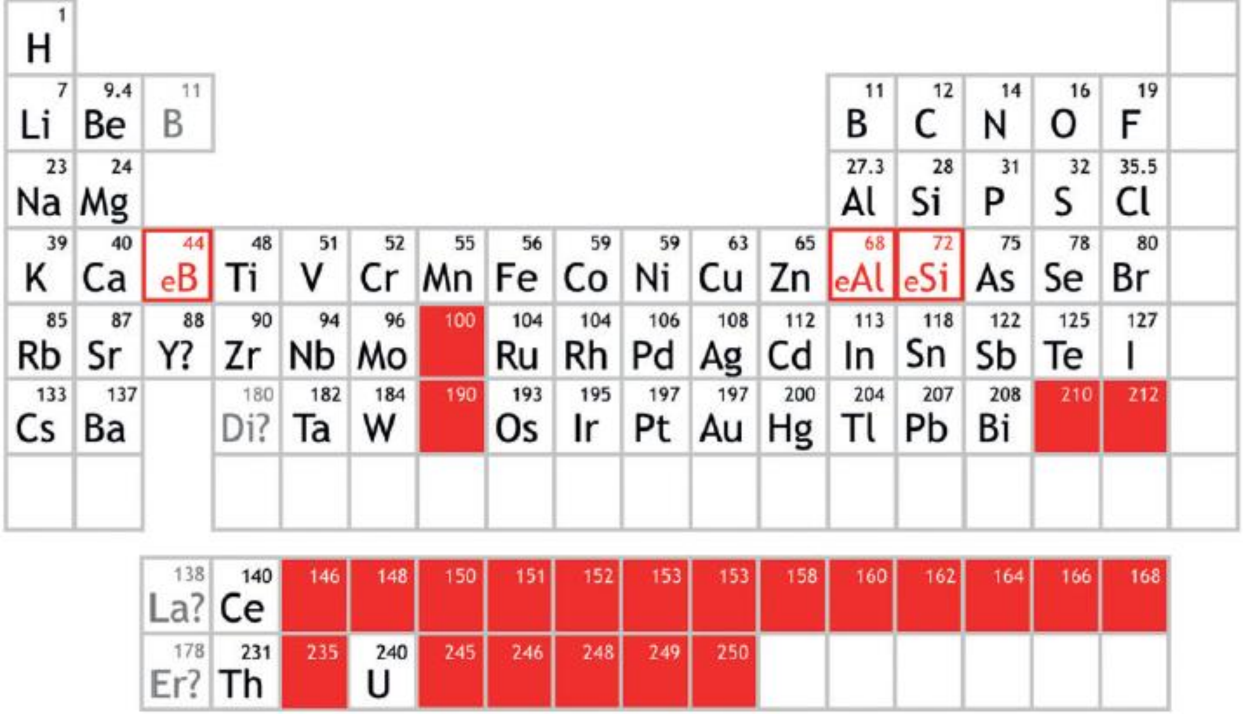



*Figure 9.* A modern-shaped Mendeleev's Table of 1871, with eka-elements printed in red e.g., eAl, and some predictive empty boxes marked in red. Boron (B) is duplicated in grey besides Be; this unusual position intends to show its relationship with eka-boron (eB, which would later be discovered and named Sc). The e-elements and

| | **Predictions** | **Discoveries** |
|---|---|---|
| | **Eka-Aluminum** | **Gallium** (discovered in 1875 by Lecoq) |
| AW | 68 | 69.9 |
| Density | 6.0 | 5.96 |
| Atomic Volume | 11.5 | 11.7 |
| | **Eka-Boron** | **Scandium** (discovered in1879 by Nilson) |
| AW | 44 | 43.79 |

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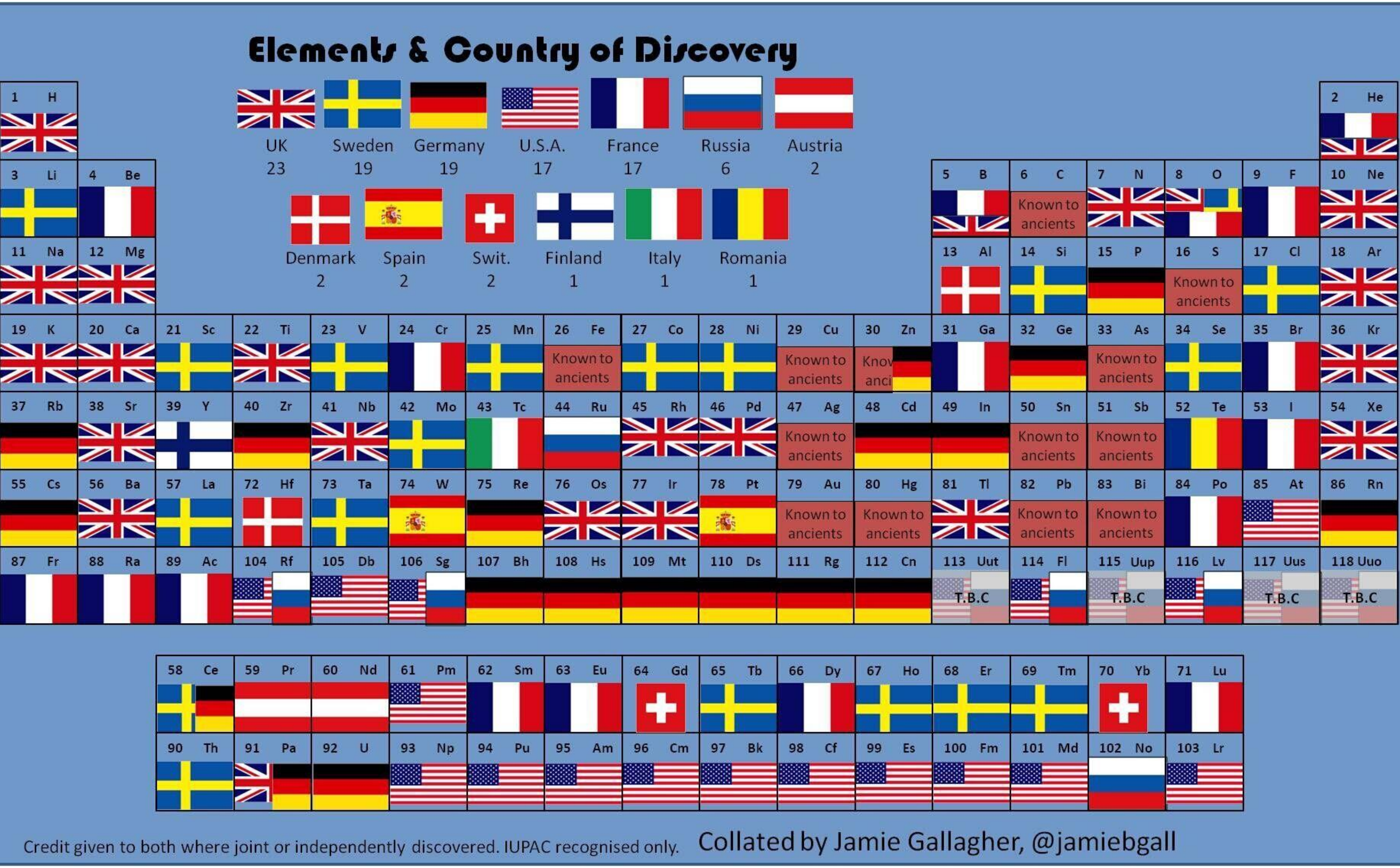


**113: Japan; 115, 117 & 118: Russia & US**

# The Latest Periodic Table

| | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 **H** hydrogen 1.008 [1.0078, 1.0082] | 2 | | Key: | | | | | | | | | 13 | 14 | 15 | 16 | 17 | 2 **He** helium 4.0026 |
| 3 **Li** lithium 6.94 [6.938, 6.997] | 4 **Be** beryllium 9.0122 | | atomic number **Symbol** name conventional atomic weight standard atomic weight | | | | | | | | | 5 **B** boron 10.81 [10.806, 10.821] | 6 **C** carbon 12.011 [12.009, 12.012] | 7 **N** nitrogen 14.007 [14.006, 14.008] | 8 **O** oxygen 15.999 [15.999, 16.000] | 9 **F** fluorine 18.998 | 10 **Ne** neon 20.180 |
| 11 **Na** sodium 22.990 | 12 **Mg** magnesium 24.305 [24.304, 24.307] | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 **Al** aluminium 26.982 | 14 **Si** silicon 28.085 [28.084, 28.086] | 15 **P** phosphorus 30.974 | 16 **S** sulfur 32.06 [32.059, 32.076] | 17 **Cl** chlorine 35.45 [35.446, 35.457] | 18 **Ar** argon 39.948 |
| 19 **K** potassium 39.098 | 20 **Ca** calcium 40.078(4) | 21 **Sc** scandium 44.956 | 22 **Ti** titanium 47.867 | 23 **V** vanadium 50.942 | 24 **Cr** chromium 51.996 | 25 **Mn** manganese 54.938 | 26 **Fe** iron 55.845(2) | 27 **Co** cobalt 58.933 | 28 **Ni** nickel 58.693 | 29 **Cu** copper 63.546(3) | 30 **Zn** zinc 65.38(2) | 31 **Ga** gallium 69.723 | 32 **Ge** germanium 72.630(8) | 33 **As** arsenic 74.922 | 34 **Se** selenium 78.971(8) | 35 **Br** bromine 79.904 [79.901, 79.907] | 36 **Kr** krypton 83.798(2) |
| 37 **Rb** rubidium 85.468 | 38 **Sr** strontium 87.62 | 39 **Y** yttrium 88.906 | 40 **Zr** zirconium 91.224(2) | 41 **Nb** niobium 92.906 | 42 **Mo** molybdenum 95.95 | 43 **Tc** technetium | 44 **Ru** ruthenium 101.07(2) | 45 **Rh** rhodium 102.91 | 46 **Pd** palladium 106.42 | 47 **Ag** silver 107.87 | 48 **Cd** cadmium 112.41 | 49 **In** indium 114.82 | 50 **Sn** tin 118.71 | 51 **Sb** antimony 121.76 | 52 **Te** tellurium 127.60(3) | 53 **I** iodine 126.90 | 54 **Xe** xenon 131.29 |
| 55 **Cs** caesium 132.91 | 56 **Ba** barium 137.33 | 57-71 lanthanoids | 72 **Hf** hafnium 178.49(2) | 73 **Ta** tantalum 180.95 | 74 **W** tungsten 183.84 | 75 **Re** rhenium 186.21 | 76 **Os** osmium 190.23(3) | 77 **Ir** iridium 192.22 | 78 **Pt** platinum 195.08 | 79 **Au** gold 196.97 | 80 **Hg** mercury 200.59 | 81 **Tl** thallium 204.38 [204.38, 204.39] | 82 **Pb** lead 207.2 | 83 **Bi** bismuth 208.98 | 84 **Po** polonium | 85 **At** astatine | 86 **Rn** radon |
| 87 **Fr** francium | 88 **Ra** radium | 89-103 actinoids | 104 **Rf** rutherfordium | 105 **Db** dubnium | 106 **Sg** seaborgium | 107 **Bh** bohrium | 108 **Hs** hassium | 109 **Mt** meitnerium | 110 **Ds** darmstadtium | 111 **Rg** roentgenium | 112 **Cn** copernicium | 113 **Nh** nihonium | 114 **Fl** flerovium | 115 **Mc** moscovium | 116 **Lv** livermorium | 117 **Ts** tennessine | 118 **Og** oganesson |

| | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 57 **La** lanthanum 138.91 | 58 **Ce** cerium 140.12 | 59 **Pr** praseodymium 140.91 | 60 **Nd** neodymium 144.24 | 61 **Pm** promethium | 62 **Sm** samarium 150.36(2) | 63 **Eu** europium 151.96 | 64 **Gd** gadolinium 157.25(3) | 65 **Tb** terbium 158.93 | 66 **Dy** dysprosium 162.50 | 67 **Ho** holmium 164.93 | 68 **Er** erbium 167.26 | 69 **Tm** thulium 168.93 | 70 **Yb** ytterbium 173.05 | 71 **Lu** lutetium 174.97 |
| 89 **Ac** actinium | 90 **Th** thorium 232.04 | 91 **Pa** protactinium 231.04 | 92 **U** uranium 238.03 | 93 **Np** neptunium | 94 **Pu** plutonium | 95 **Am** americium | 96 **Cm** curium | 97 **Bk** berkelium | 98 **Cf** californium | 99 **Es** einsteinium | 100 **Fm** fermium | 101 **Md** mendelevium | 102 **No** nobelium | 103 **Lr** lawrencium |

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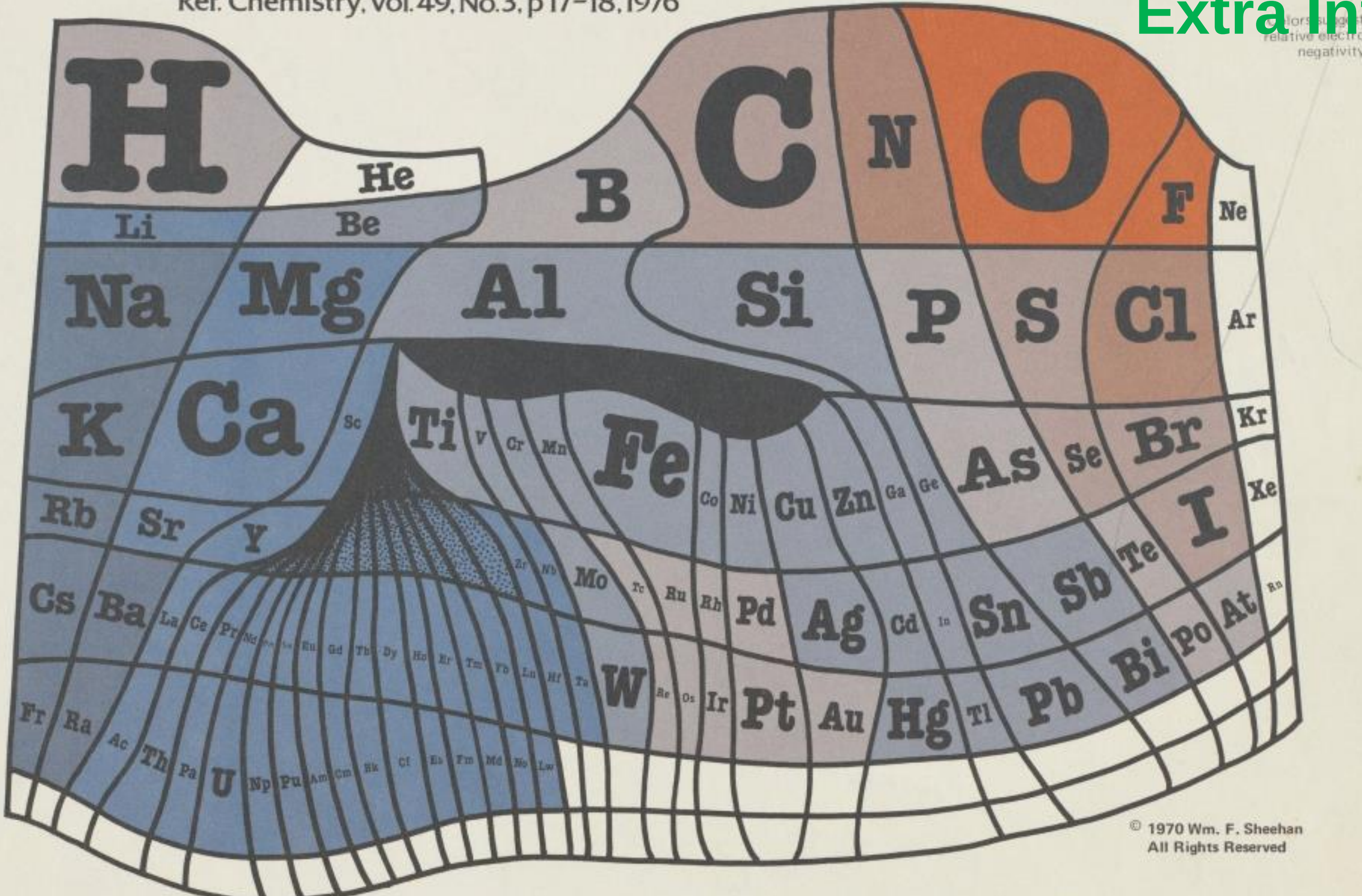
Useful interactive ones: https://www.ptable.com
https://pubchem.ncbi.nlm.nih.gov/periodic-table

# The Elements According to Relative Abundance

A Periodic Chart by Prof. Wm. F. Sheehan, University of Santa Clara, CA 95053

Ref. Chemistry, Vol. 49, No. 3, p 17–18, 1976

Extra Info:






Roughly, the size of an element's own niche ("I almost wrote square") is proportioned to its abundance on Earth's surface, and in addition, certain chemical similarities (e.g., Be and Al, or B and Si) are suggested by the positioning of neighbors. The chart emphasizes that in real life a chemist will probably meet O, Si, Al, . . . and that he better do something about it. Periodic tables based upon elemental abundance would, of course, vary from planet to planet. . . W.F.S.

*NOTE: TO ACCOMMODATE ALL ELEMENTS SOME DISTORTIONS WERE NECESSARY, FOR EXAMPLE SOME ELEMENTS DO NOT OCCUR NATURALLY.*

# ESSENTIAL ELEMENTS FOR HUMANS

There are 118 elements in the periodic table, but which of them are essential for human life? Here we zero in on the ones we can't live without and the roles they play.

**Extra Info:**

### THE ELEMENTAL COMPOSITION OF THE HUMAN BODY BY MASS

| OXYGEN | CARBON | HYDROGEN | NITROGEN | OTHERS[a] |
|---|---|---|---|---|
| O 65% | C 18% | H 10% | N 3% | 4% |

a Includes Ca, P, K, S, Na, Cl, Mg, B, Cr, Co, Cu, F, I, Fe, Mn, Mo, Se, Si, Sn, V, and Zn.

## BUILDING BLOCKS

H C N O P S


These elements (except phosphorus) are found in amino acids, the building blocks of proteins. With the exception of sulfur, they all also combine to make up DNA, our genetic code.

## ENZYMES

Mg Mn Cu Zn Se Mo


Metal ions help many enzymes in the body function. Enyzmes have many important roles in the body, including in respiration, digestion, metabolism, and the immune system.

## NERVES AND CONTROL

Na Cl K Ca I

Sodium, potassium, and calcium ions play roles in transmitting nerve signals. Chloride ions regulate fluid in and out of cells. The body uses iodine to make hormones that regulate metabolism.

## BONES AND TEETH

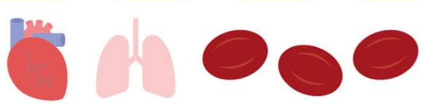
O P Ca Mn



Bones and teeth are mainly calcium phosphate. Calcium is essential for the growth of healthy teeth and bones. Without manganese, bones are spongier and break more easily.

## BLOOD

C O Fe Co



Iron in hemoglobin carries oxygen from the lungs to the body's cells. And it carries carbon dioxide back to the lungs. Cobalt, found in vitamin B-12, is essential for making red blood cells.

## RESPIRATION AND ENERGY

C N O P


Our cells use the oxygen we breathe for respiration. Respiration produces adenosine triphosphate (ATP, shown), a molecular energy source for our cells.

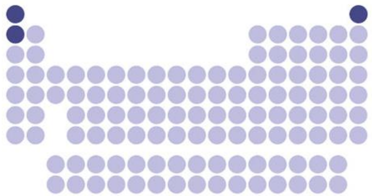
PERIODIC GRAPHICS

# THE ORIGINS OF THE ELEMENTS

The 118 elements in the periodic table don't all have the same backstory. Here, we examine how different elements were created, according to physicists and chemists.

**Extra Info:**

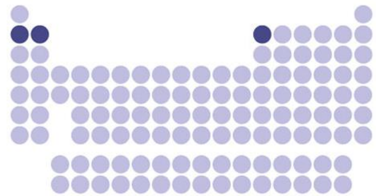
## THE BIG BANG



H He Li

The lightest elements were made by nuclear reaction chains between 10 s and 20 min after the big bang. Hydrogen and helium in particular were made in large amounts.

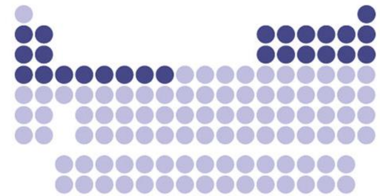
## COSMIC RAYS



Li Be B

When cosmic rays in space hit the nuclei of elements like carbon or nitrogen, they cause those elements to fragment into lighter elements like lithium, beryllium, and boron.

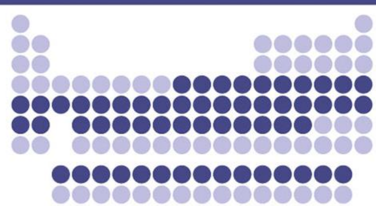
## FUSION IN STARS



He → Fe

Fusion reactions inside stars generate the energy that stars radiate. They produce elements from helium up to iron. Creating heavier elements isn't possible through fusion.

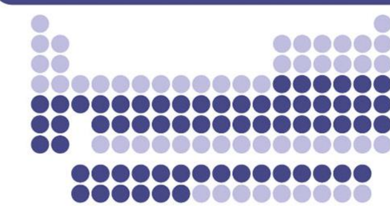
## THE S-PROCESS



Co → Bi

The slow neutron-capture process (s-process) occurs in aging stars over thousands of years. Atoms capture neutrons and undergo β decay to produce new element isotopes.

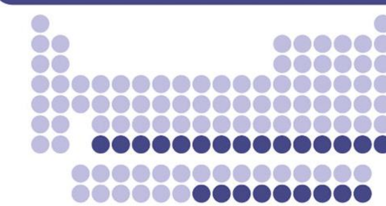
## THE R-PROCESS



Ga → Pu

In the rapid neutron-capture process (r-process), atoms capture many neutrons at once and undergo β decay to form new element isotopes. It occurs in neutron star collisions.

## SYNTHETIC ELEMENTS



Am → Og

The heaviest elements have been created artificially on Earth in nuclear reactors or particle accelerators. These elements are unstable and decay into lighter elements rapidly.

Note: Elements are highlighted where isotopes of that element are created by the process discussed. Not all isotopes created are stable.

PERIODIC GRAPHICS

# Periodic Trends

# Periodicity

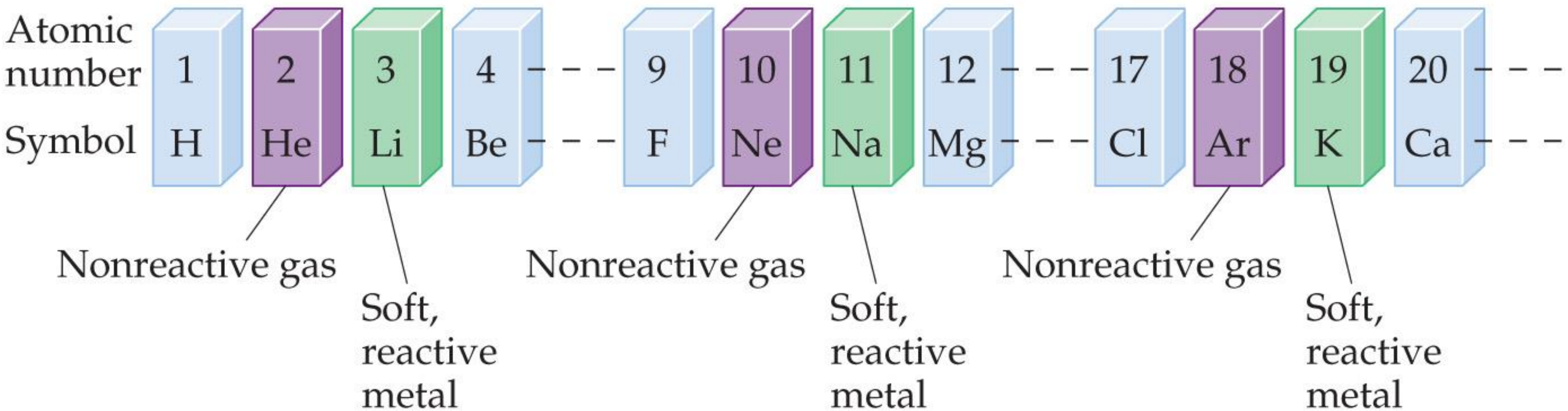
- Periodicity: the **repetitive** pattern of a **property** for elements based on atomic number.
- For example:

  Sizes of atoms and ions;

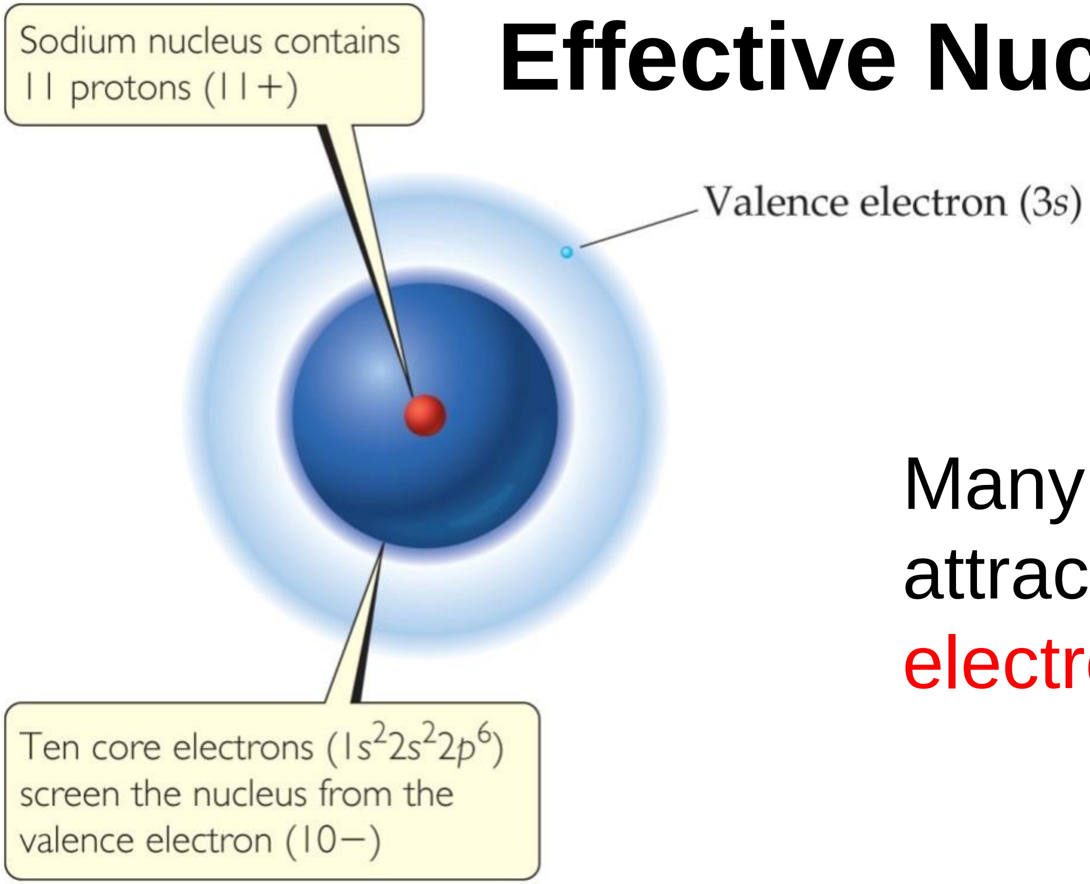
  Ionization energy (I.E.);

  Electron affinity (E.A.);

  Chemical property.



# Effective Nuclear Charge ($Z_{eff}$)




$1s^2 2s^2 2p^6 3s^1$

Many properties depend on attractions between **valence electrons** & the nucleus.

- In a many-electron atom, **electrons** are simultaneously both **attracted** to the nucleus & **repelled** by the other electrons.
- **Effective nuclear charge** (force): **one electron** (either valence electron or core electron) experiences **net** effect of the **attractions** & **repulsions**.

The effective nuclear charge, $Z_{\text{eff}}$:

$$Z_{\text{eff}} = Z - \boldsymbol{S}$$

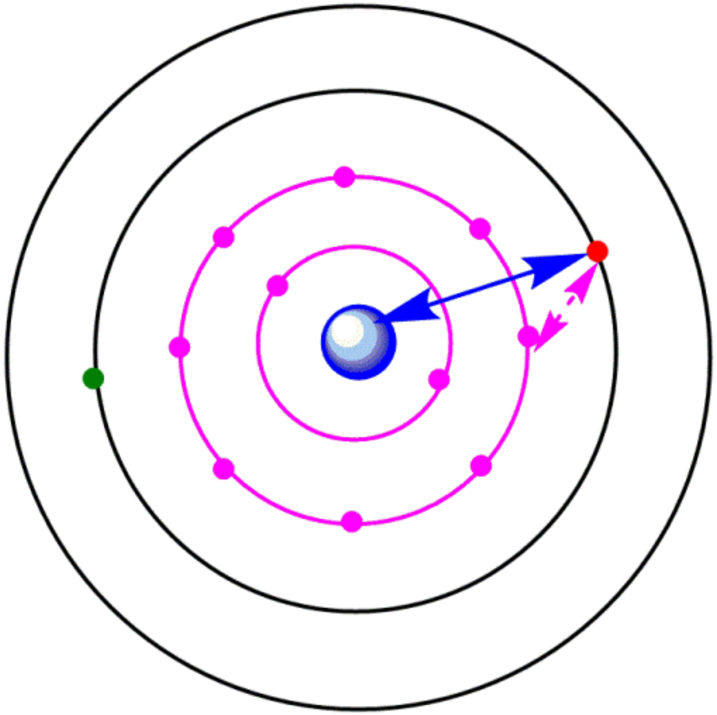
where $Z$ is the atomic number & $S$ is a *screening* （屏蔽） *constant*, (can be **simply** approximated by the number of its **core/inner electrons**).

e.g. $\boldsymbol{Z_{\text{eff}}}$ for one of the **valence electrons**:

| | | |
|---|---|---|
| Si | $1s^2 2s^2 2p^6 3s^2 3p^2$ | $Z_{\text{eff}} \sim 14 - 10 = 4$ |
| P | $1s^2 2s^2 2p^6 3s^2 3p^3$ | $Z_{\text{eff}} \sim 15 - 10 = 5$ |
| S | $1s^2 2s^2 2p^6 3s^2 3p^4$ | $Z_{\text{eff}} \sim 16 - 10 = 6$ |

$$Z_{eff} = Z - S$$

*S* is usually close to the number of it **core/inner electrons**.



**Mg:**
12 protons
12 electrons

**$Z_{eff}$ for the red electron (net attraction with the protons)**

~ 12 - 10 = 2

(12)protons-(1)electron attraction

(10)core electrons-(1)electron repulsion **(major)**

(1)valence electrons-(1)electron repulsion **(minor)**

1. Any of one **3s** electrons ($n = 3$): $Z_{eff} \sim 2$
2. Any of one **second-shell** electrons ($n = 2$; 2s or 2p):
$$Z_{eff} \sim 12 - 2 \sim 10$$
3. Any of one **first-shell (1s)** electrons ($n = 1$):
$$Z_{eff} \sim 12 - 0 \sim 12$$

# Screening Constant: Slater's Rules

1. Electrons in **higher groups (higher energy level, >*n*)** do **not** shield those in lower groups (≤ n).

2. For **ns or np valence electrons** :
a. Electrons in the **same ns or np group (same energy level, *n*)** contribute **0.35**, **except the 1s**, where **0.30** works better.
b. Electrons in the **n–1 group** contribute **0.85**.
c. Electrons in the **n–2 or lower groups** contribute **1.00**.

3. For **nd and nf valence electrons**:
a. Electrons in the **same nd or nf group** contribute **0.35**.
b. Electrons in **groups to the left** contribute **1.00**.



J. C. Slater, *Phys. Rev.* **1930**, *36*, 57.

$$Z_{\text{eff}} = Z - S$$

e.g. Oxygen $1s^2 2s^2 2p^4$

$(1s^2)(2s^2 2p^4)$

For each of the 2p electron,

$$Z_{\text{eff}} = Z - S$$

$$= 8 - (2 \times \mathbf{0.85}) - (\mathbf{5} \times \mathbf{0.35}) = 4.55$$

$\mathbf{1}s^2$ $\mathbf{2}s^2\mathbf{2}p^{\mathbf{3}}$

$$Z_{eff} = Z - S$$

e.g. Nickel $1s^2 2s^2 2p^6 3s^2 3p^6 3d^8 4s^2$

$(1s^2)(2s^2 2p^6)(3s^2 3p^6)(3d^8)(4s^2)$

For each of the 3d electron,

$Z_{eff} = Z - S$

$= 28 - (18 \times 1.00) - (7 \times 0.35) = 7.55$

$1s^2 2s^2 2p^6 3s^2 3p^6 \quad 3d^7$

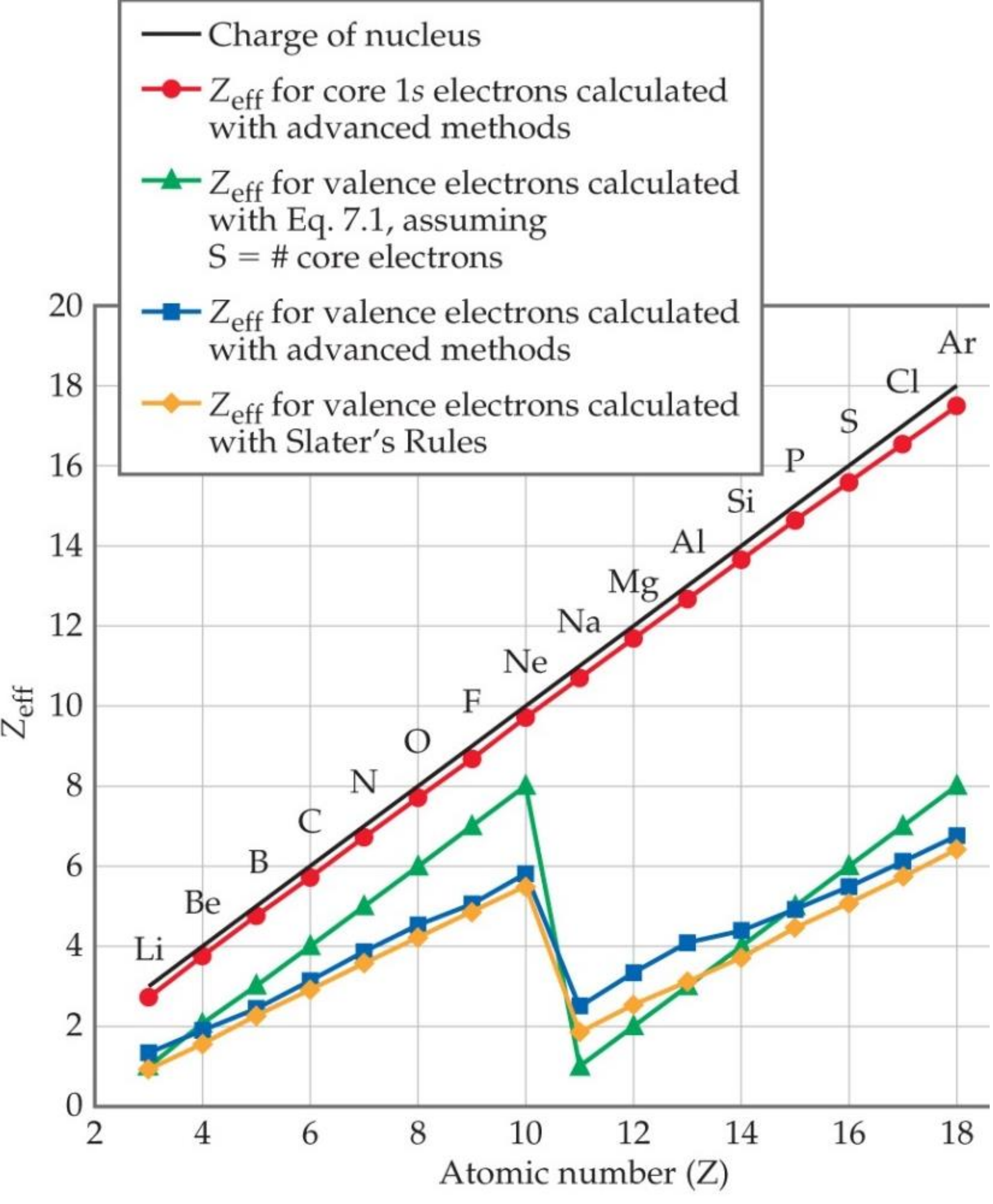
For each of the 4s electron,

$Z_{eff} = Z - S$

$= 28 - (10 \times 1.00) - (16 \times 0.85) - (1 \times 0.35)$

$= 4.05$

$1s^2 2s^2 2p^6 \quad 3s^2 3p^6 3d^8 \quad 4s^1$



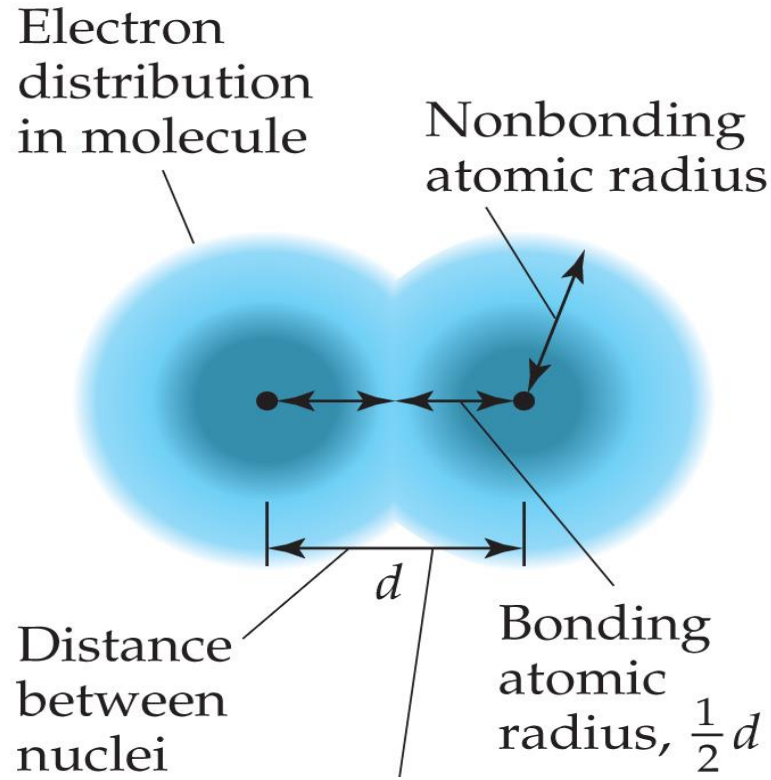

1. $Z_{eff}$ **increases from left to right** of the periodic table (number of proton **increases**).

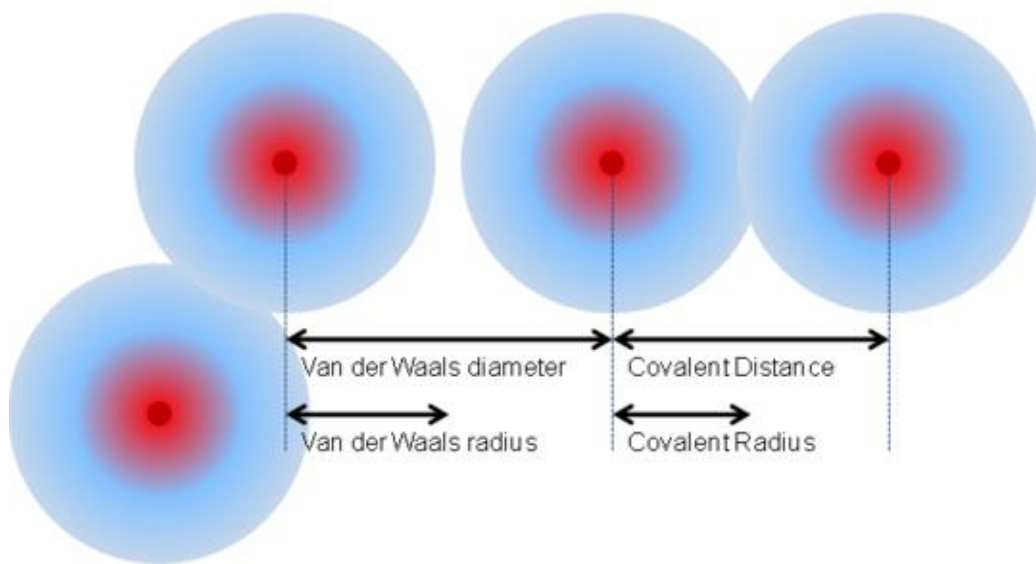
2. $Z_{eff}$ slightly **increases down a group** (**more diffuse core electron** cloud is **less** able to **screen** the valence electrons).

# Size of an Atom

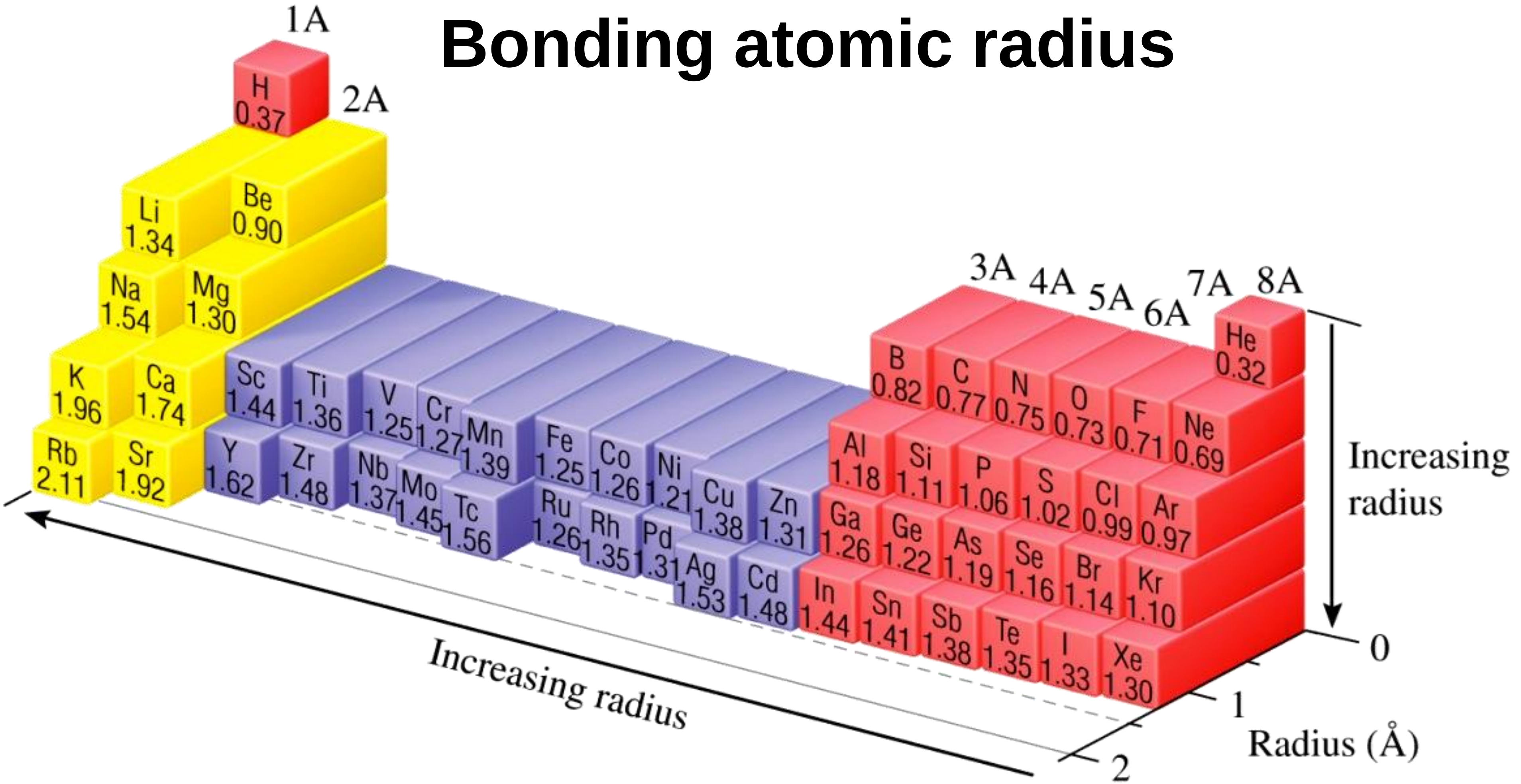
**Bonding atomic radius** (covalent radius): **one half** of the **distance between covalently bonded nuclei within a molecule**.

**Nonbonding atomic radius (or van der Waals** 范德华 **radius): half of the shortest distance separating two nonbonding nuclei** during a collision of **atoms/molecules**.



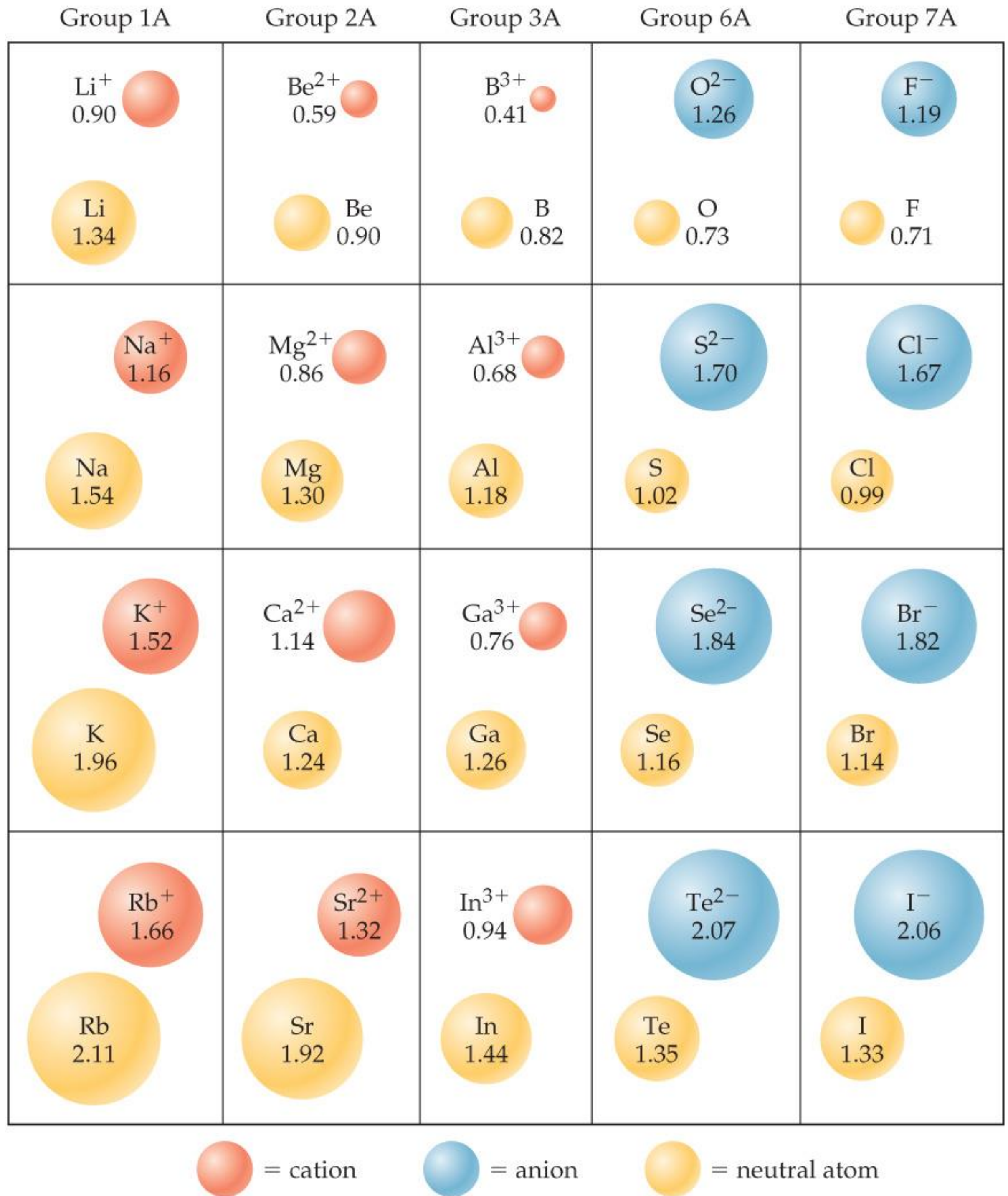



# Bonding atomic radius



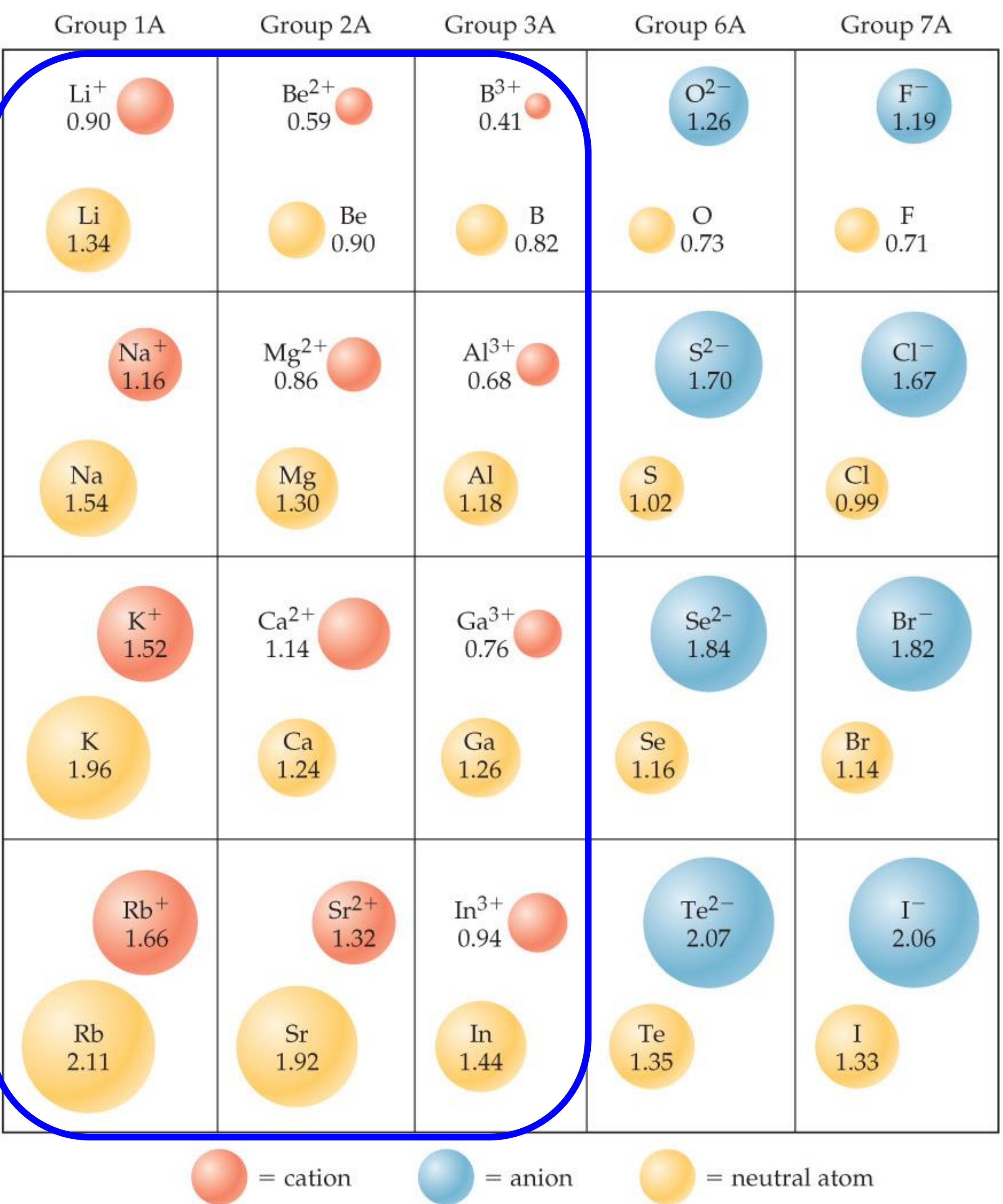

The bonding atomic **radius** tends to **decrease from left to right** across a row (due to **increasing** $Z_{eff}$).
They **increase from top to bottom** of a column (due to the **increasing *n* value; *NOT minor $Z_{eff}$ effect!*)**.

# Sizes of Ions



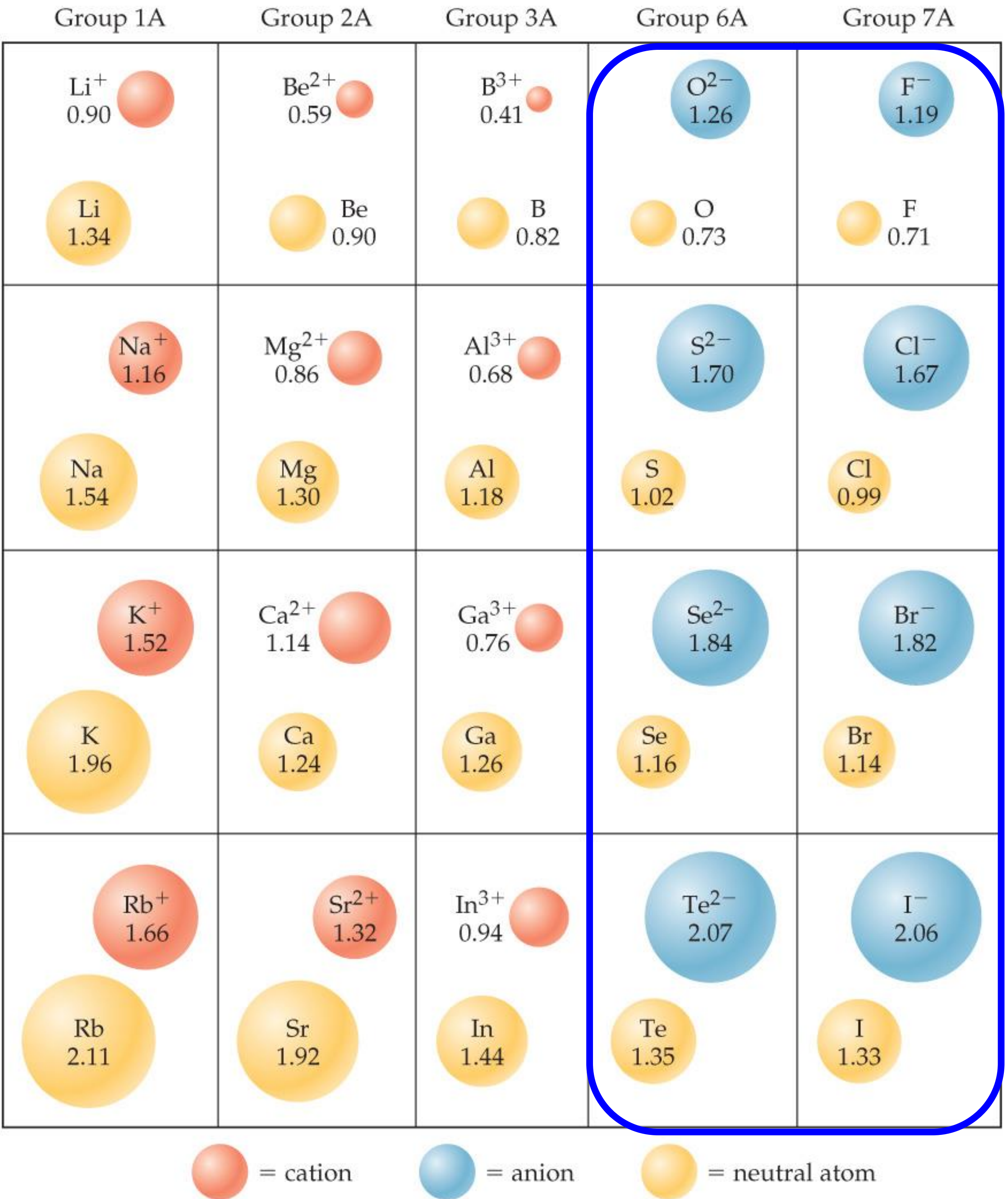

Ionic size (ionic radius) depends on

1. $Z_{eff}$;
2. the number of electrons;
3. the orbitals ($n$ value or type of the orbital).




$$Z_{eff} = Z - S$$

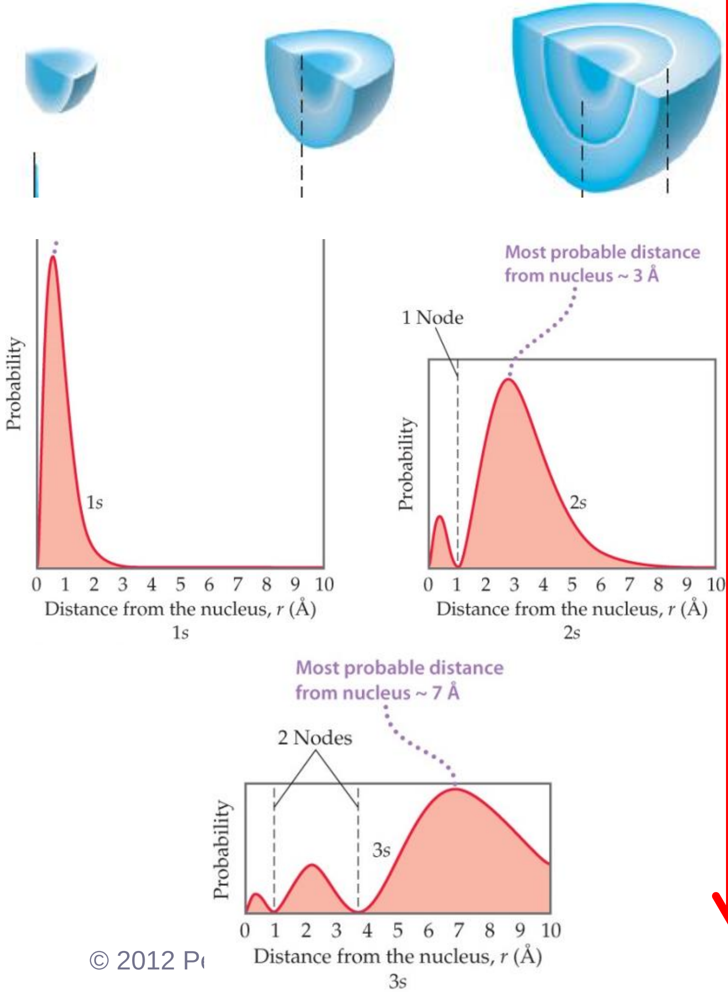
**Cations are smaller** than their parent neutral atoms: one (or many) outermost electron(s) is(are) removed &, thus, **repulsions** between electrons are **reduced**.



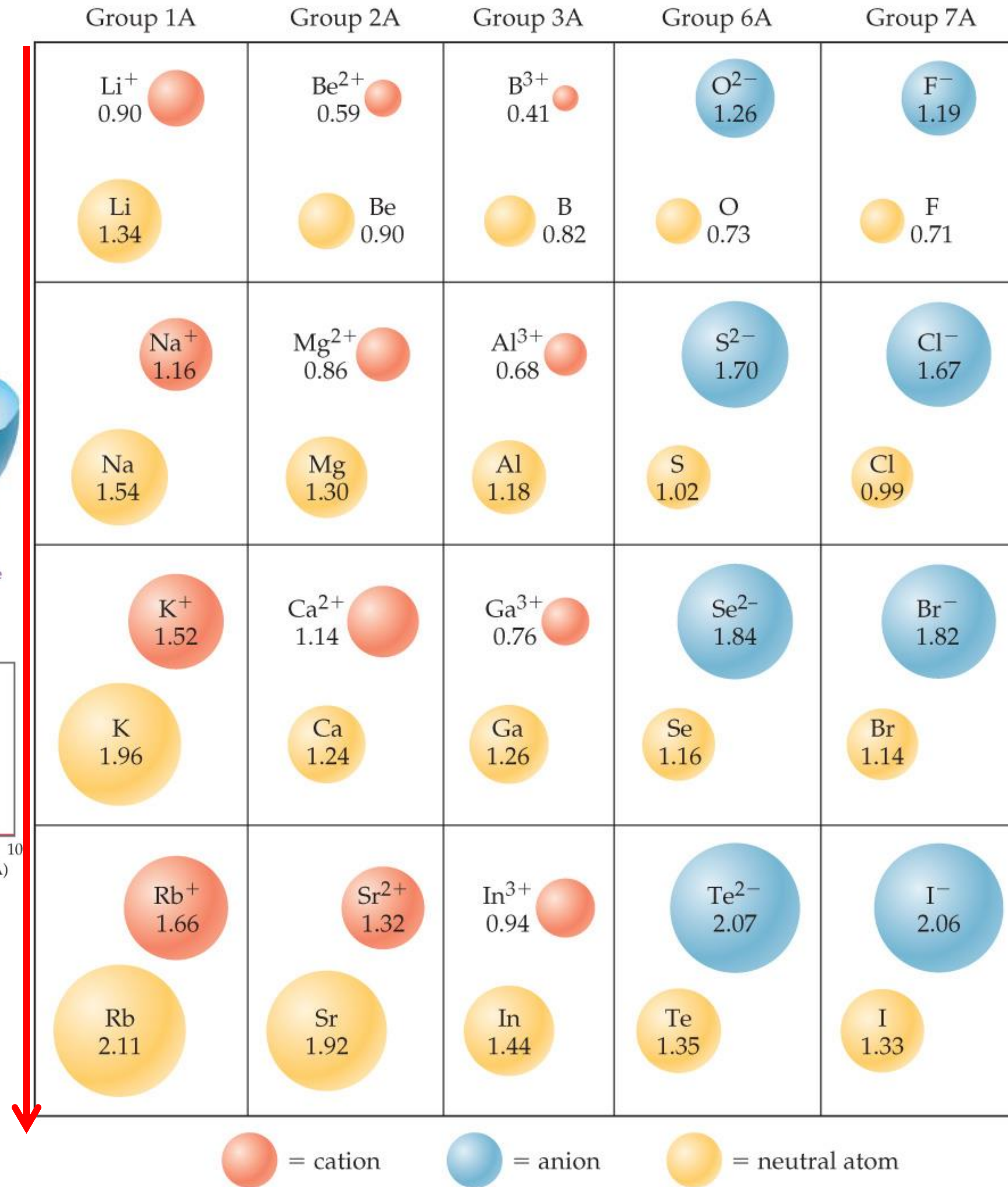

$$Z_{eff} = Z - S$$

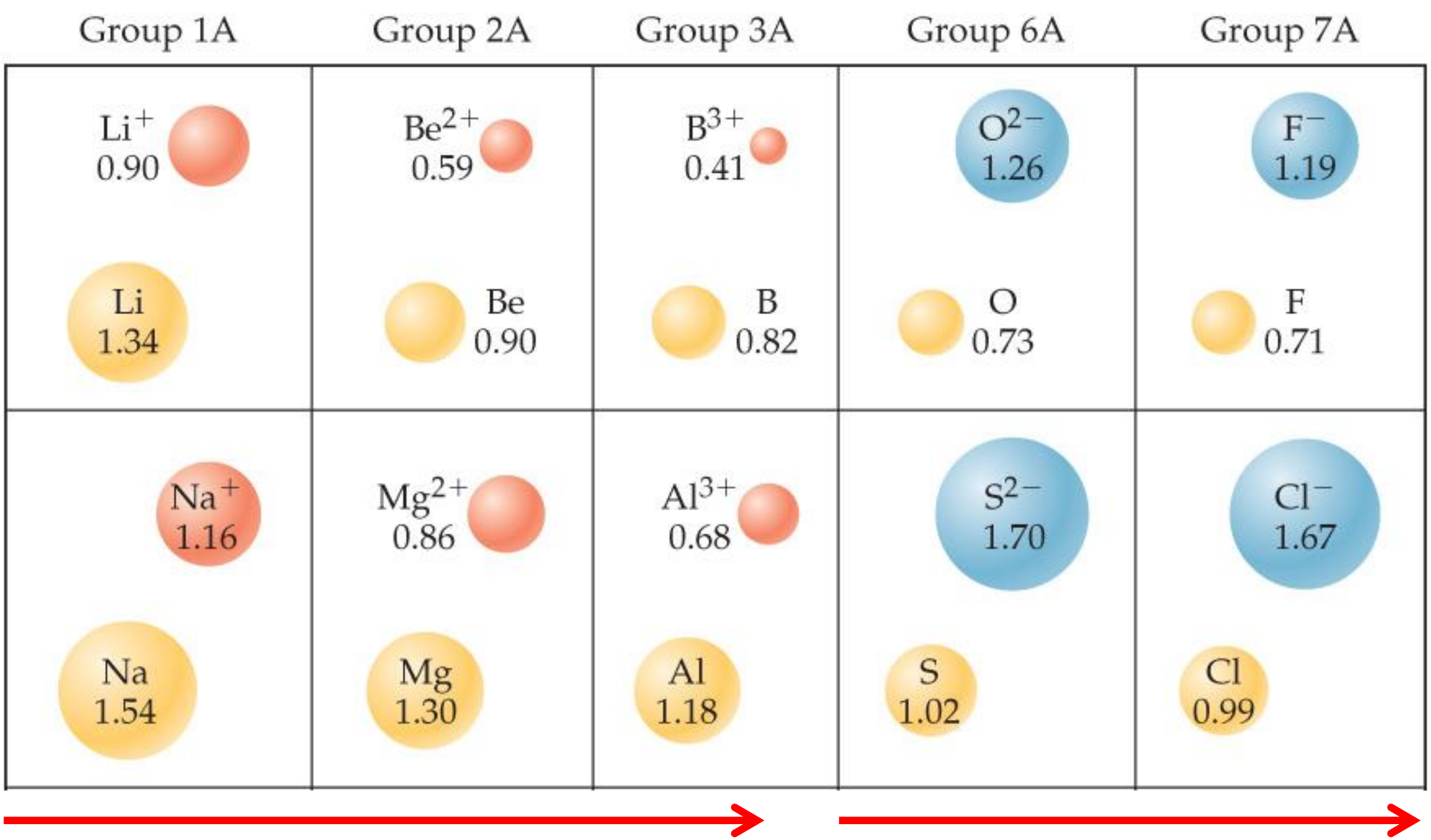
**Anions are larger** than their parent atoms: electron(s) is(are) added &, thus, **repulsions** between electrons are **increased**.

Ions **increase** in **size** when **down a group,** due to the **increasing *n* value**.








- In an **isoelectronic** (等电子的) **series**, ions have the **same** number of electrons. e.g. 1) $O^{2-}$, $F^{-}$, $Na^{+}$, $Mg^{2+}$, $Al^{3+}$; 2) $Li^{+}$, $Be^{2+}$, $B^{3+}$; 3) $S^{2-}$, $Cl^{-}$
- Ionic size decreases with increasing nuclear charge (the more positive, the stronger attraction with electrons).



$$Z_{eff} = Z - S$$

# Extra Info:

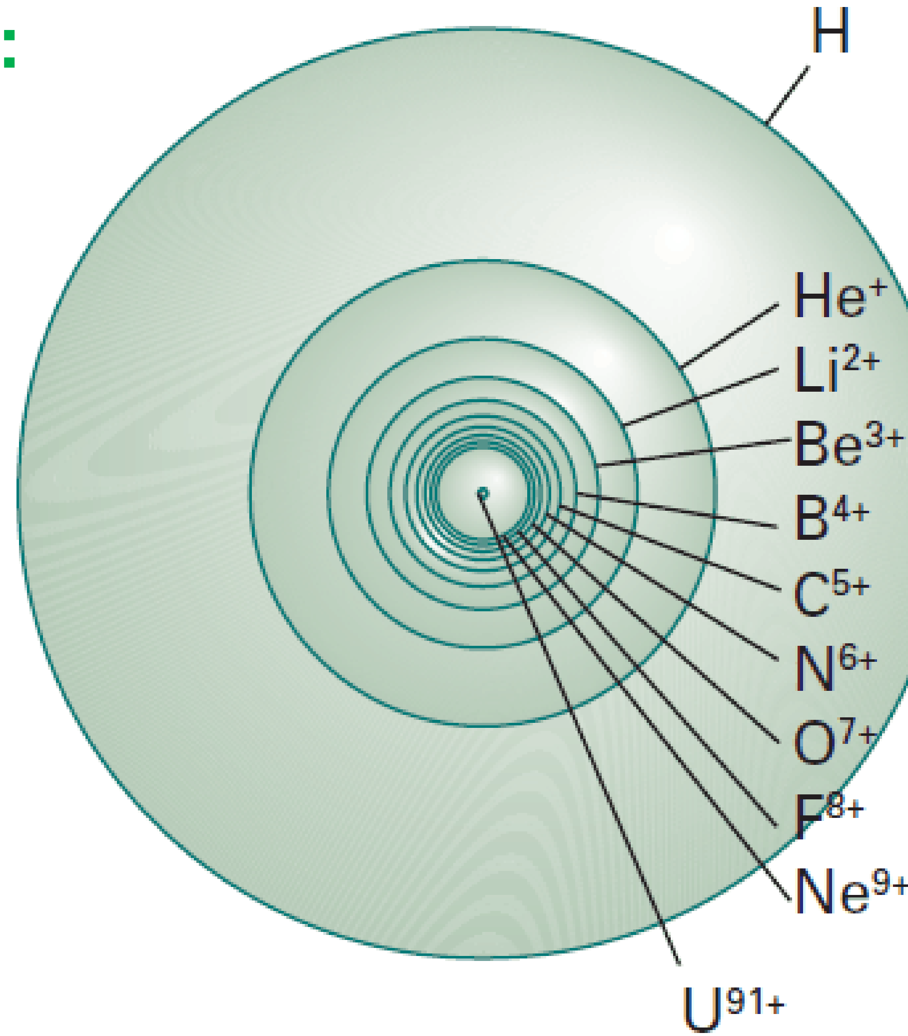



**Fig. 9.14** A representation of the most probable radii of a variety of one-electron atoms and ions.

# Ionization Energy (IE, 电离能)

**Ionization energy**: the minimum amount of **energy** required to **remove an electron** from the **ground state** of a **gaseous** atom or ion.

$$\text{Na(g)} \longrightarrow \text{Na}^{+}\text{(g)} + e^{-}$$

$$[\text{Ne}]3s^1 \qquad\qquad [\text{He}]2s^22p^6$$

The **first** ionization energy: energy required to remove **the first electron**.

The **second** ionization energy: energy required to remove **the second electron**.

$$\text{Na}^{+}\text{(g)} \longrightarrow \text{Na}^{2+}\text{(g)} + e^{-}$$

$$[\text{He}]2s^22p^6 \qquad\qquad [\text{He}]2s^22p^5$$

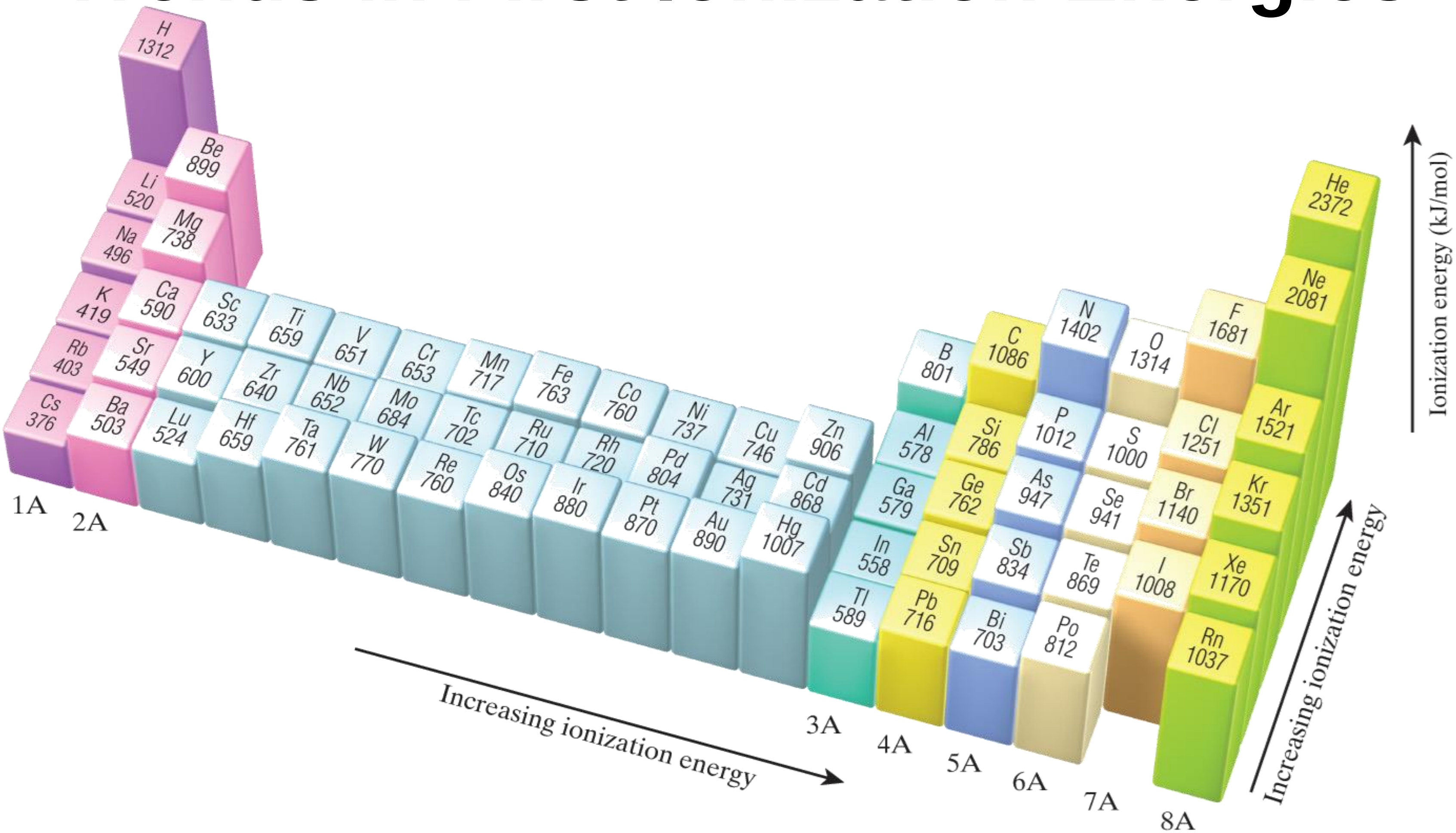
- Requires **more energy** to remove each **successive**（连续的）**electron ($I_1 < I_2 < I_3 < I_4$)**.

- After all valence electrons are removed, the ionization energy increases **significantly** (**removal** of **core electrons**, much closer to the nucleus & stronger attraction; break stable noble-gas configuration).

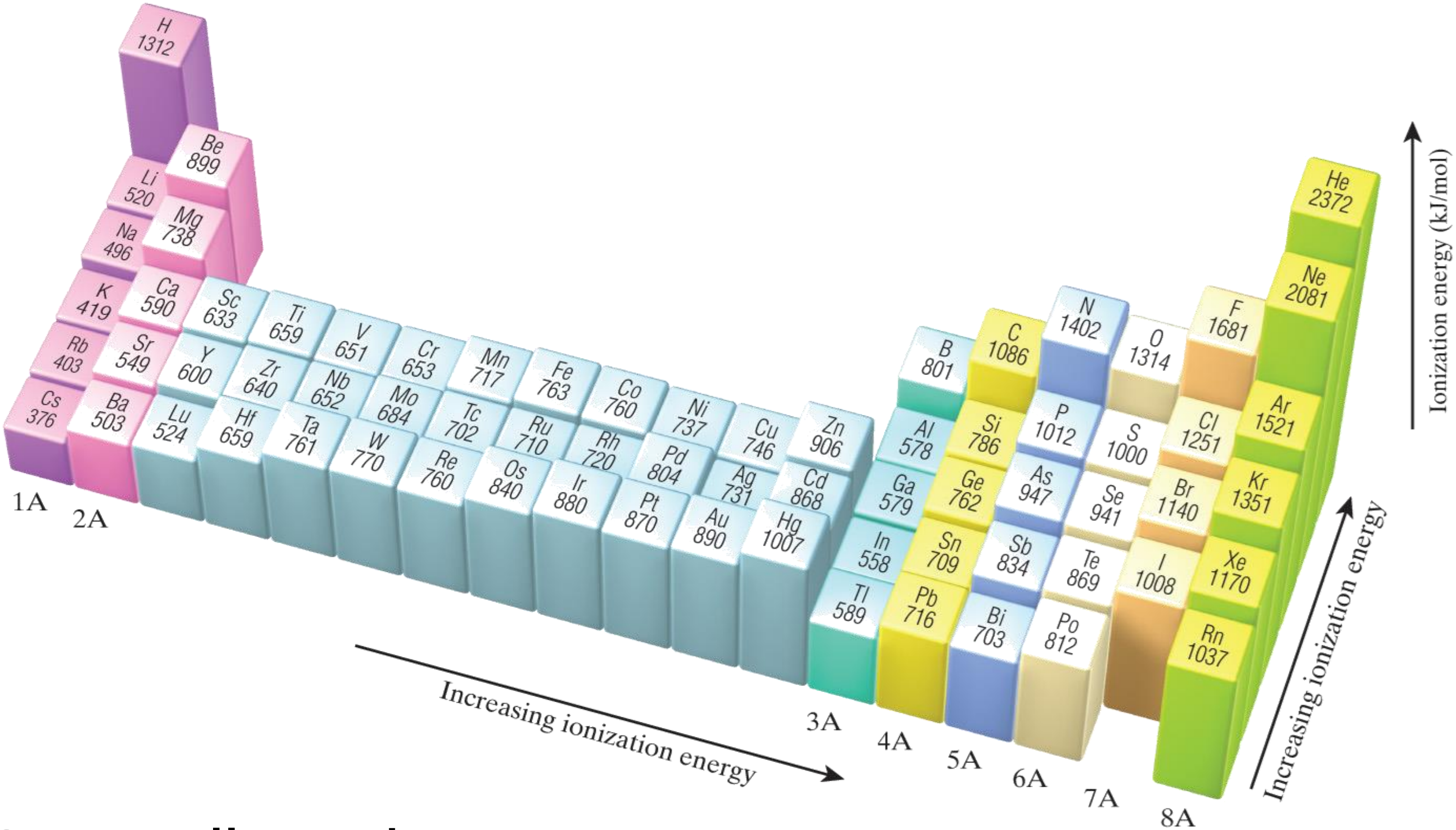
**able 7.2 Successive Values of Ionization Energies, *I*, for the Elements Sodium through Argon (kJ/mol)**

| Element | $I_1$ | $I_2$ | $I_3$ | $I_4$ | $I_5$ | $I_6$ | $I_7$ |
|---|---|---|---|---|---|---|---|
| Na | 496 | 4562 | | | (inner-shell electrons) | | |
| Mg | 738 | 1451 | 7733 | | | | |
| Al | 578 | 1817 | 2745 | 11,577 | | | |
| Si | 786 | 1577 | 3232 | 4356 | 16,091 | | |
| P | 1012 | 1907 | 2914 | 4964 | 6274 | 21,267 | |
| S | 1000 | 2252 | 3357 | 4556 | 7004 | 8496 | 27,107 |
| Cl | 1251 | 2298 | 3822 | 5159 | 6542 | 9362 | 11,018 |
| Ar | 1521 | 2666 | 3931 | 5771 | 7238 | 8781 | 11,995 |

# Trends in First Ionization Energies

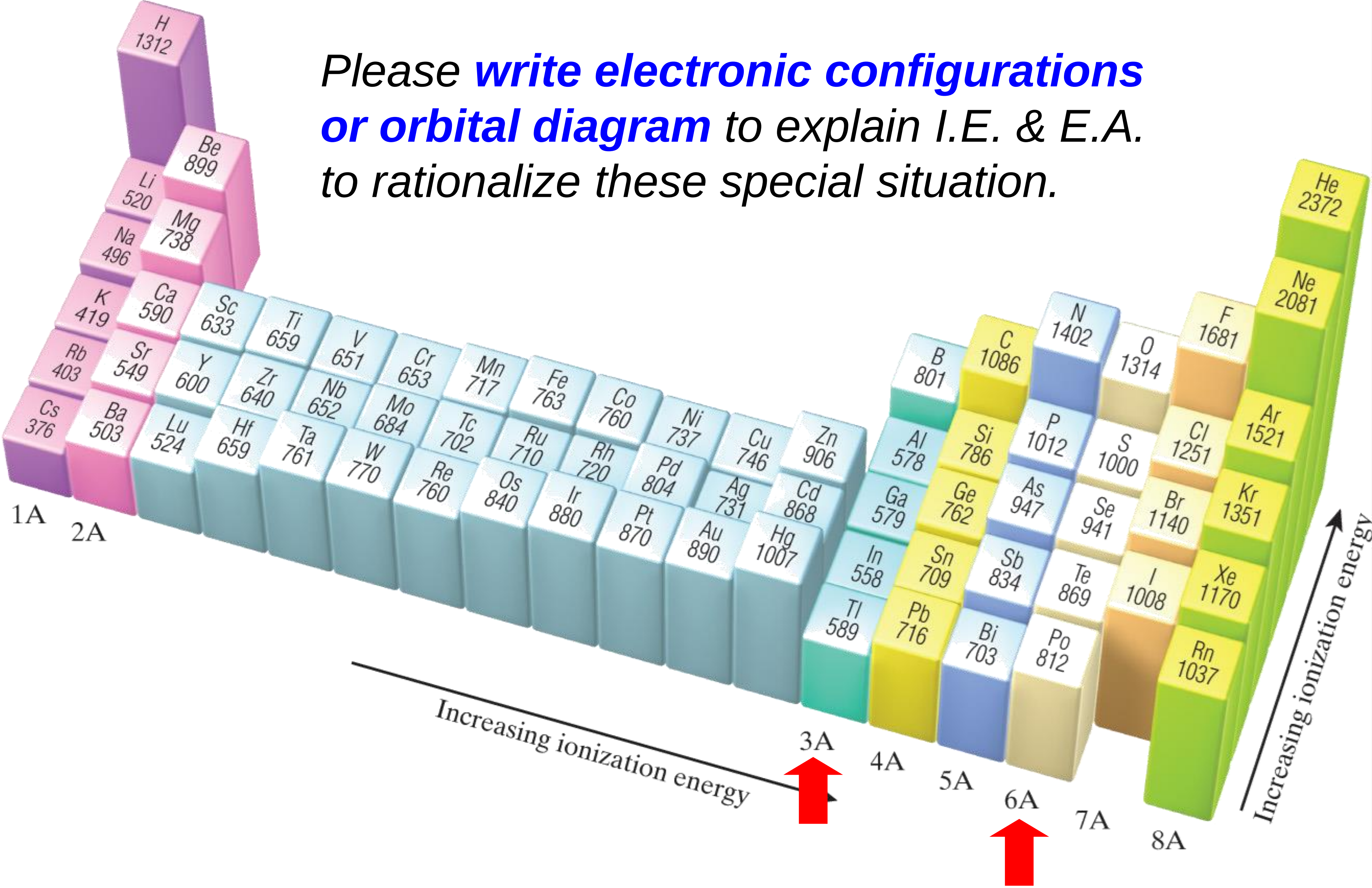



- When **down a group (larger *n* value)**, **less energy** is required to remove the first electron: the valence electrons are **farther** from the nucleus (**weaker attraction)**.

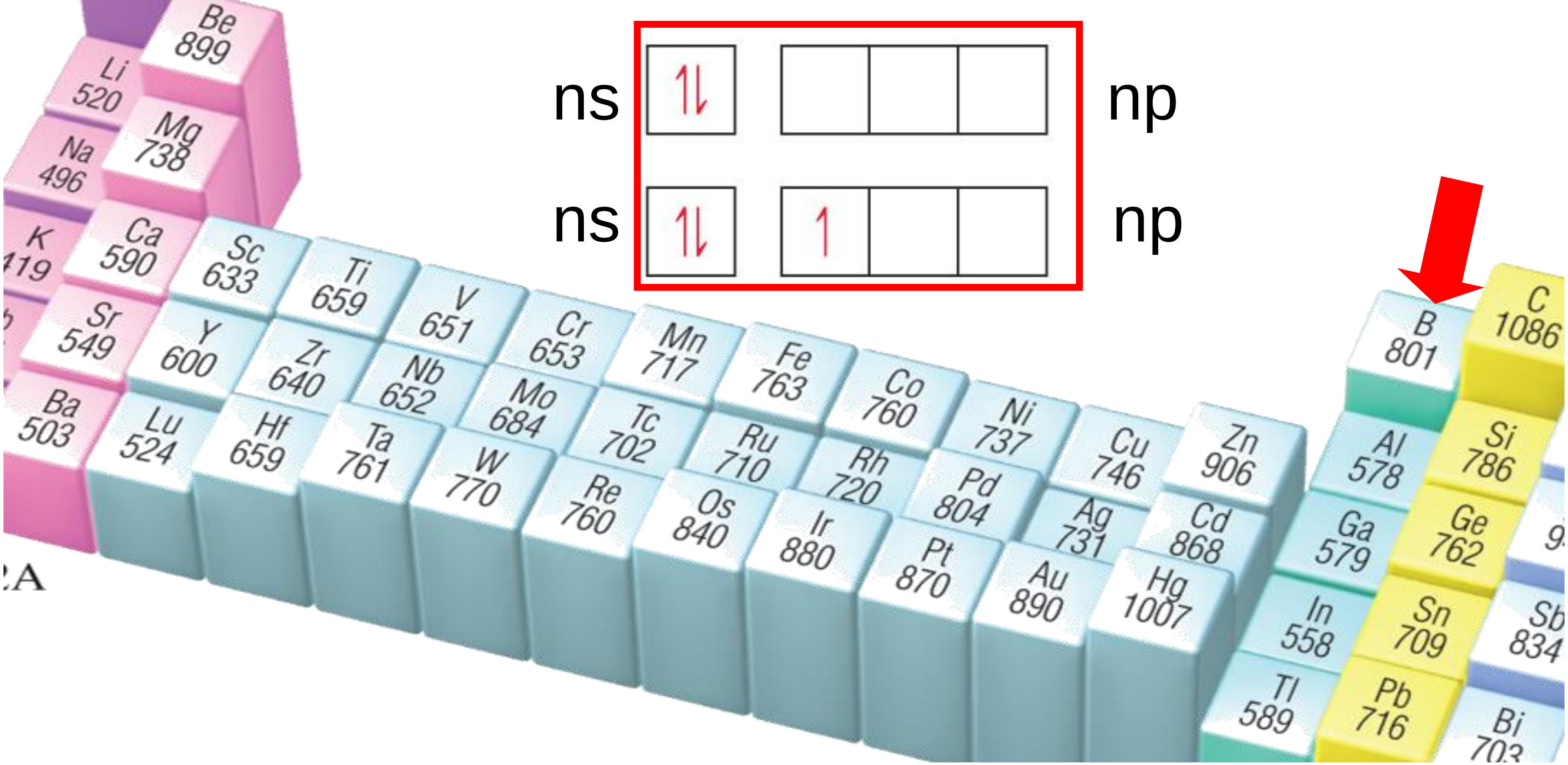



- Generally, when **across a row**, **more energy** is required to remove an electron (**larger** $Z_{\text{eff}}$, more attraction).
- The *s*- and *p*-block elements: a larger range of values for $I_1$. (The *d*-block generally increases slowly; the *f*-block elements show only small variations.)

*Please **write electronic configurations or orbital diagram** to explain I.E. & E.A. to rationalize these special situation.*



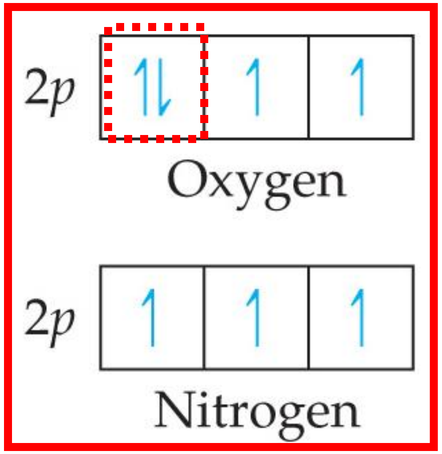

However, there are two apparent discontinuities（不连续）in this trend.

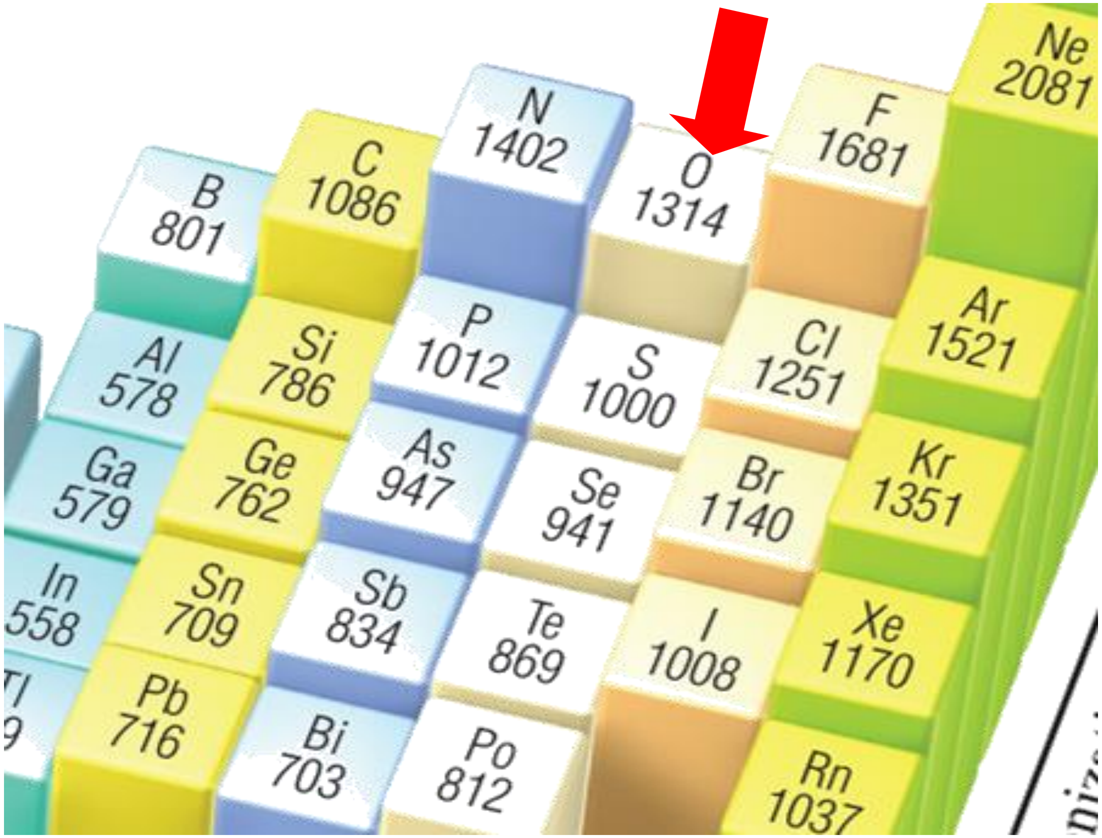



- The first discontinuity between Groups IIA & IIIA.

- The electron is removed from a *p* orbital (**farther** from the nucleus) rather than an *s* orbital: **less attraction** between **the nucleus & the p electron** for Group III A.

**$ns^2np^1 \rightarrow ns^2$**




Group **VIA**:

**$ns^2np^4 \rightarrow ns^2np^3$**

Group **VA**:

**$ns^2np^3 \rightarrow ns^2np^2$**

- The second discontinuity between Groups VA & VIA.
- The electron removed comes from a singly occupied orbital for Group **VA** and from a **doubly** occupied orbital for Group **VIA** e.g. N ($1s^22s^2p^{\mathbf{3}}$) vs. O($1s^22s^2p^{\mathbf{4}}$); Repulsion from the other electron in the **same orbital** promotes the electron removal for O.

Electrons are **removed** from the occupied orbitals with the **highest principal quantum number** (***n***) first:

Li ($1s^2 2s^1$) → $Li^+$ ($1s^2$) + $e^-$

Fe ($[Ar]3d^6\mathbf{4s^2}$) → $Fe^{2+}$ ($[Ar]3d^6$) + $2e^-$

$Fe^{2+}$ ($[Ar]3d^6$) → $Fe^{3+}$ ($[Ar]3d^5$) + $e^-$

For orbitals with the **same *n*** value (same shell), electrons are **removed** from those with the **highest angular momentum quantum number** (***l***) first:

Sn ($[Kr]4d^{10}5s^2\mathbf{5p^2}$) → $Sn^{2+}$ ($[Kr]4d^{10}\mathbf{5s^2}$) + $2e^-$
→ $Sn^{4+}$ ($[Kr]4d^{10}$) + $4e^-$

# Electron Affinity (EA, 电子亲合能)

**Electron affinity**: the **energy change** for the **addition** of an electron to a **gaseous** atom:

$$\mathrm{Cl(g)} + e^{-} \longrightarrow \mathrm{Cl^{-}(g)}$$

[Ne]$3s^2 3p^5$ [Ne]$3s^2 3p^6$

# Trends in Electron Affinity

| 1A | 2A | 3A | 4A | 5A | 6A | 7A | 8A |
|---|---|---|---|---|---|---|---|
| **H** −73 | | | | | | | **He** > 0 |
| **Li** −60 | **Be** > 0 | **B** −27 | **C** −122 | **N** > 0 | **O** −141 | **F** −328 | **Ne** > 0 |
| **Na** −53 | **Mg** > 0 | **Al** −43 | **Si** −134 | **P** −72 | **S** −200 | **Cl** −349 | **Ar** > 0 |
| **K** −48 | **Ca** −2 | **Ga** −30 | **Ge** −119 | **As** −78 | **Se** −195 | **Br** −325 | **Kr** > 0 |
| **Rb** −47 | **Sr** −5 | **In** −30 | **Sn** −107 | **Sb** −103 | **Te** −190 | **I** −295 | **Xe** > 0 |



In general, electron affinity becomes **more exothermic** (more stable anions) when going from **left to right** across a row (larger $Z_{eff}$, larger attraction).

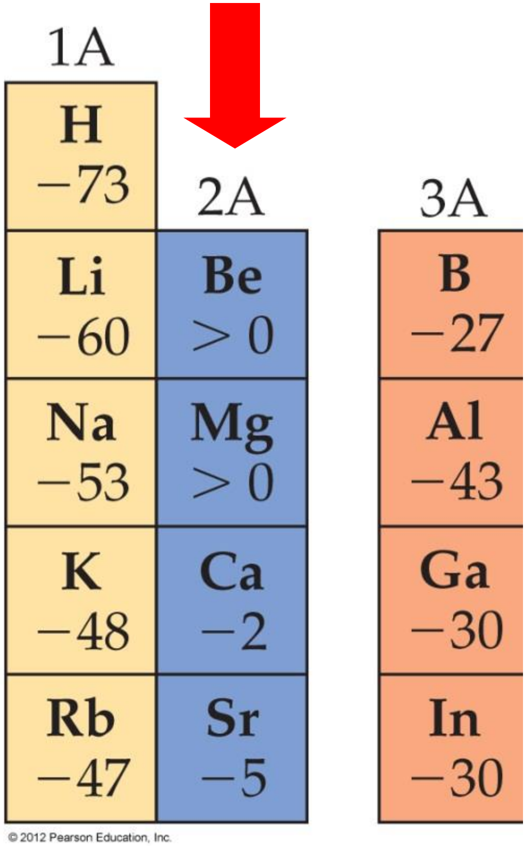
More **negative** EA, **easier** to accept an electron.

| 1A | 2A | 3A | 4A | 5A | 6A | 7A | 8A |
|---|---|---|---|---|---|---|---|
| **H** −73 | | | | | | | **He** > 0 |
| **Li** −60 | **Be** > 0 | **B** −27 | **C** −122 | **N** > 0 | **O** −141 | **F** −328 | **Ne** > 0 |
| **Na** −53 | **Mg** > 0 | **Al** −43 | **Si** −134 | **P** −72 | **S** −200 | **Cl** −349 | **Ar** > 0 |
| **K** −48 | **Ca** −2 | **Ga** −30 | **Ge** −119 | **As** −78 | **Se** −195 | **Br** −325 | **Kr** > 0 |
| **Rb** −47 | **Sr** −5 | **In** −30 | **Sn** −107 | **Sb** −103 | **Te** −190 | **I** −295 | **Xe** > 0 |

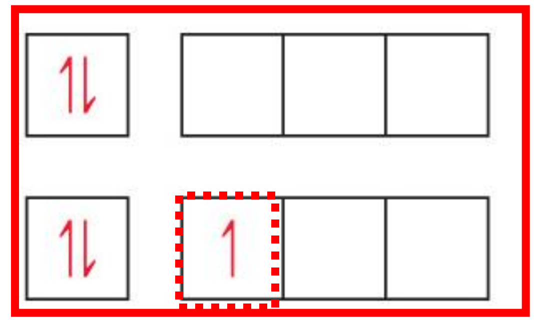


For EA, there are again two discontinuities: Groups **IIA** & **VA**).

(For IE trend, there are two discontinuities:
**Group IIIA** → Group IIA; **Group VIA** → Group VA)




$ns^2 \rightarrow ns^2np^1$

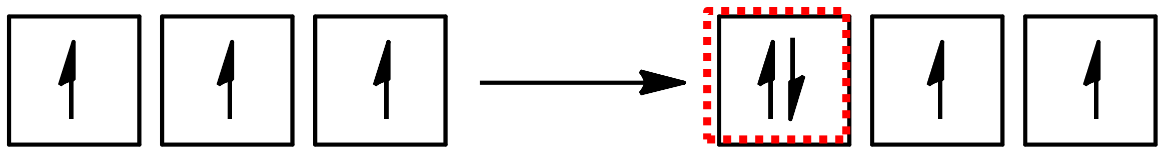


- The first occurs between Groups IA and IIA.

- The added electron must go in a ***p*** **orbital (higher-energy)**, **not a lower-energy *s* orbital**. The electron in the p orbital is **farther** from the nucleus (weaker interaction) and thus EA is relatively less favorable.

| 4A | 5A | 6A |
|---|---|---|
| C<br>−122 | N<br>> 0 | O<br>−141 |
| Si<br>−134 | P<br>−72 | S<br>−200 |
| Ge<br>−119 | As<br>−78 | Se<br>−195 |
| Sn<br>−107 | Sb<br>−103 | Te<br>−190 |

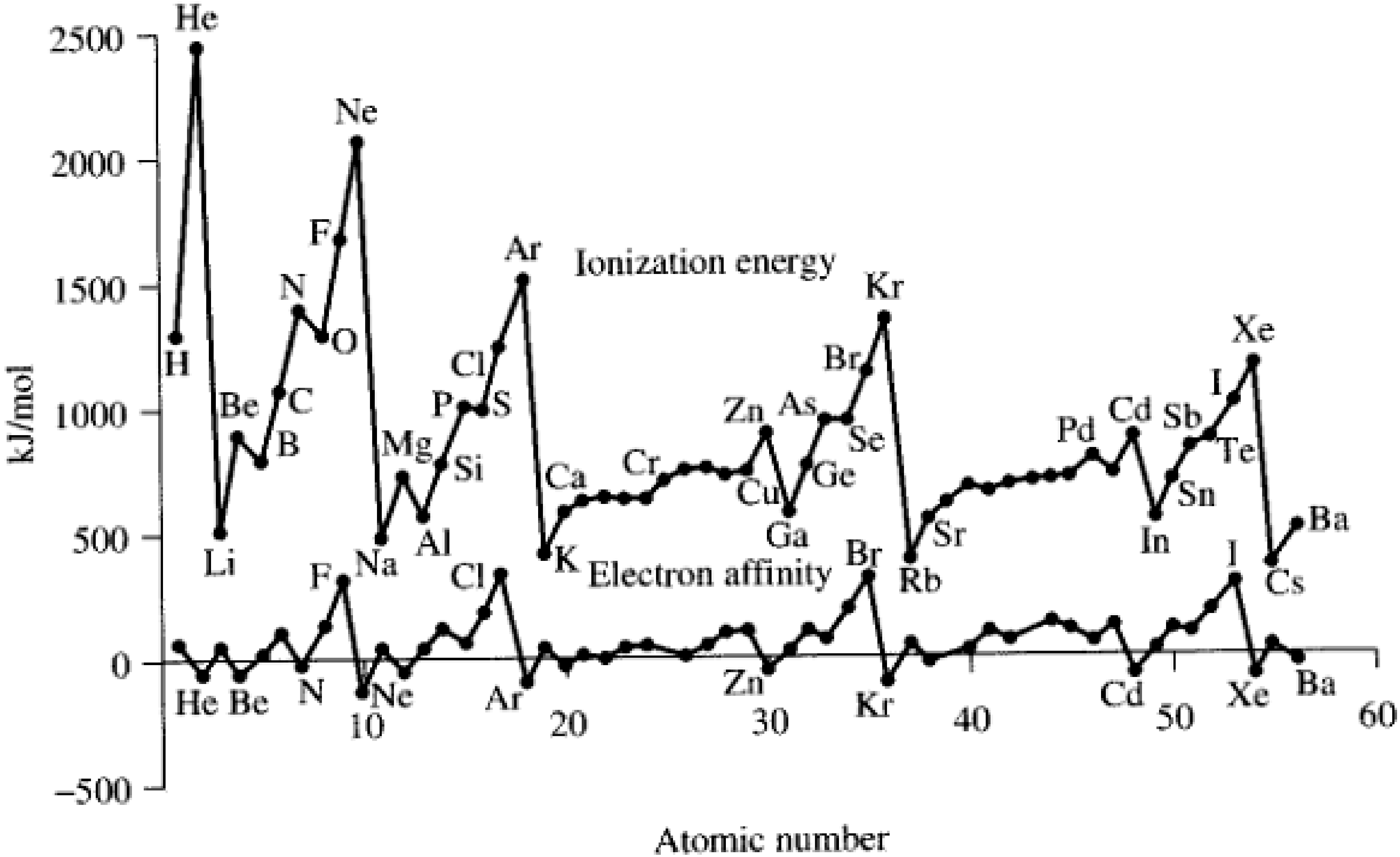
$ns^2np^3 \rightarrow ns^2np^4$



- The second discontinuity between Groups IVA & VA.

- Group VA has **no empty orbitals**. The **extra electron** must go in an **singly occupied orbital**, creating **more repulsion**, and thus EA is relatively less favorable.

# Trends in Ionization Energy & (opposite sign) Electron Affinity



The effective nuclear charge felt by an atom's valence electrons (X) going from left to right and (Y) going down a column on the Periodic Table.

a. X = increases   Y = increases
b. X = increases   Y = decreases
c. X = decreases   Y = increases
d. X = decreases   Y = decreases

The correct order of increasing atomic radius (smallest $\rightarrow$ largest) is

a. Na < Mg < K < Rb.
b. Mg < Na < K < Rb.
c. Rb < K < Na < Mg.
d. Rb < K < Mg < Na.

The statements below refer to ionic radii. Which statement is FALSE?

a. $Br^{1-}$ is larger than $Cl^{1-}$.
b. $Se^{2-}$ is larger than $Br^{1-}$.
c. $K^{1+}$ is larger than $Ca^{2+}$.
d. $Na^{1+}$ is larger than $K^{1+}$.

Two ions are isoelectronic if they have the same

a. charge.
b. number of protons.
c. number of electrons.
d. number of neutrons.

The correct order of increasing first ionization energy (smallest → largest) is

a. Na < Ca < Al < Sn.
b. Na < Al < Ca < Sn.
c. Na < Al < Sn < Ca.
d. Ca < Na < Sn < Al.

The correct order of increasing electron affinity (most negative → least negative) is

a. O < Cl < B < C.
b. O < Cl < C < B.
c. Cl < O < C < B.
d. Cl < O < B < C.

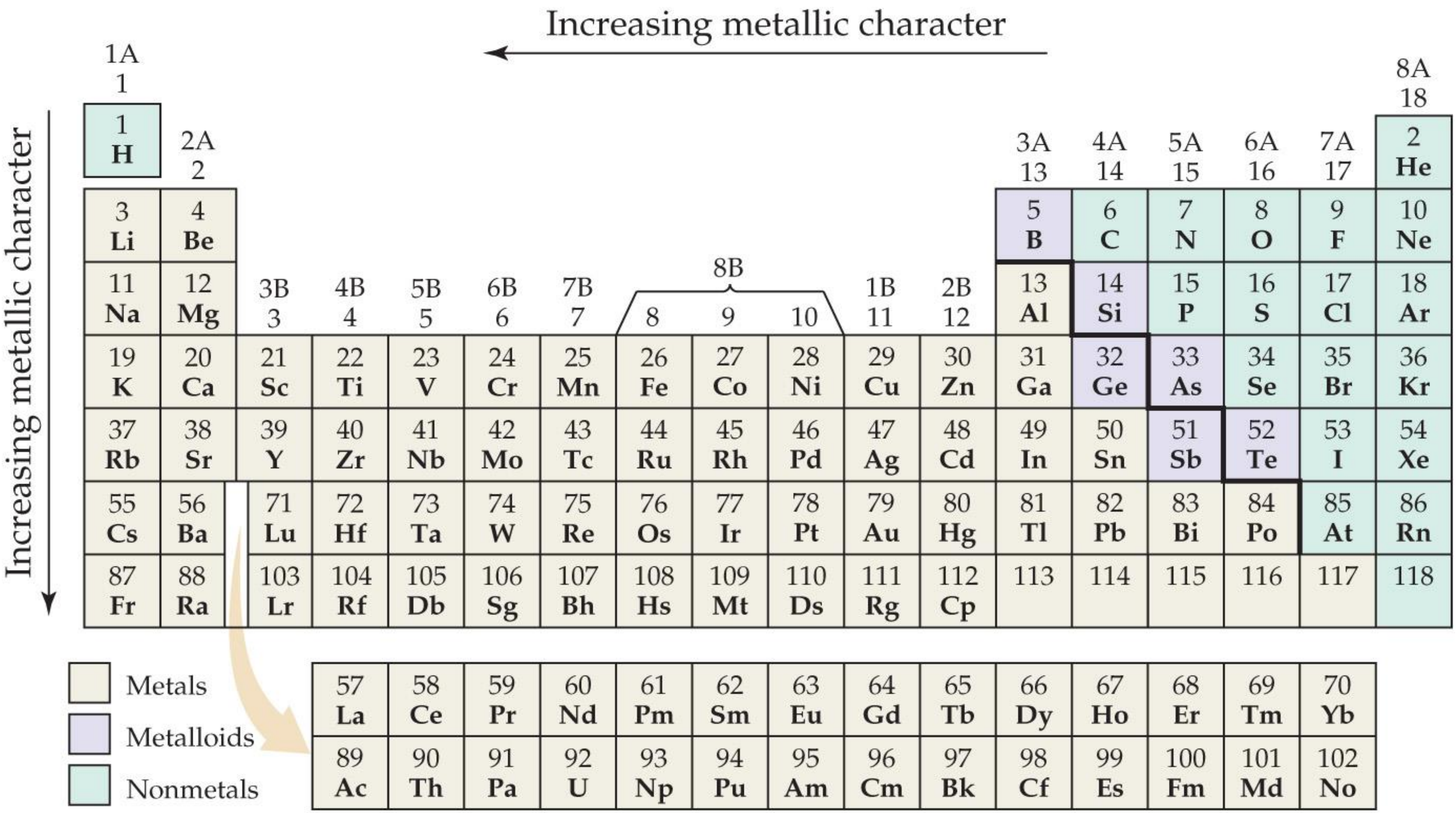
Light can be used to ionize atoms and ions. Which of the two processes shown in Equations 7.2 and 7.3 requires shorter-wavelength radiation?

$$Na(g) \longrightarrow Na^{+}(g) + e^{-} \qquad [7.2]$$

$$Na^{+}(g) \longrightarrow Na^{2+}(g) + e^{-} \qquad [7.3]$$

A. First ionization step, because it takes more energy and hence shorter wavelength.
B. First ionization step, because it takes less energy and hence shorter wavelength.
C. Second ionization step, because it takes more energy and hence shorter wavelength.
D. Second ionization step, because it takes less energy and hence shorter wavelength.

# Properties of Metal, Nonmetals, and Metalloids（类金属）



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# Metals versus Nonmetals

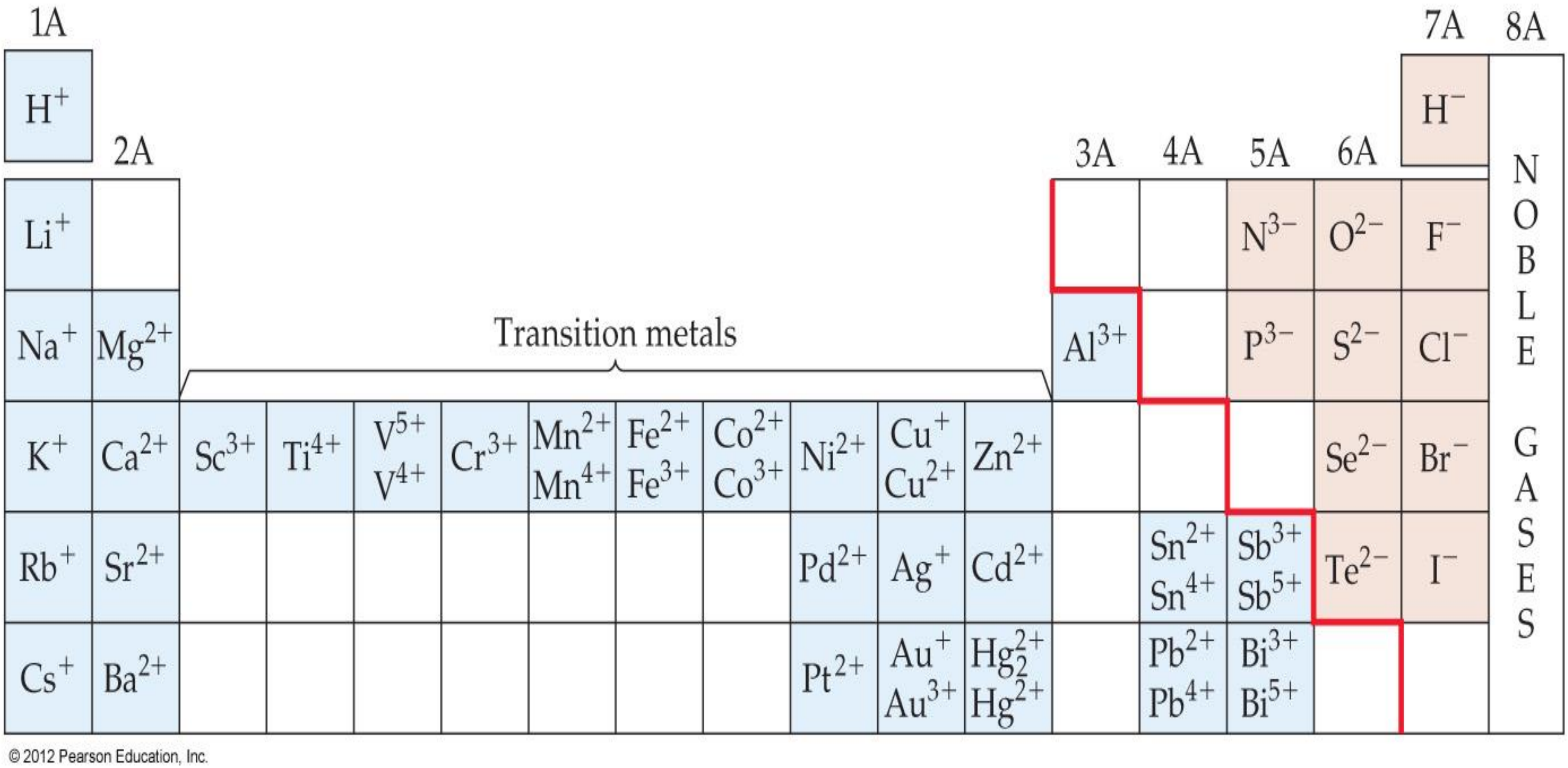
| Metals |
|---|
| Have a shiny luster; various colors, although most are silvery |
| Solids are malleable and ductile |
| Good conductors of heat and electricity |
| Most metal oxides are ionic solids that are basic |
| Tend to form cations in aqueous solution |

**Extensible & flexible**

| Nonmetals |
|---|
| Do not have a luster; various colors |
| Solids are usually brittle; some are hard, some are soft |
| Poor conductors of heat and electricity |
| Most nonmetal oxides are molecular substances that form acidic solutions |
| Tend to form anions or oxyanions in aqueous solution |

Differences between metals and nonmetals tend to revolve around these properties.

- **Metals (lower IE)** tend to form **cations**.
- **Nonmetals (higher IE & more negative EA)** tend to form **anions**.



# Metals

Metals tend to be lustrous(有光泽的), malleable(可锻的), ductile(有延展性的), and good conductors of heat and electricity.

- Compounds formed between metals and nonmetals tend to be **ionic**.
- Metal oxides tend to be basic.


Nickle oxide (NiO), nitric acid ($HNO_3$), and water

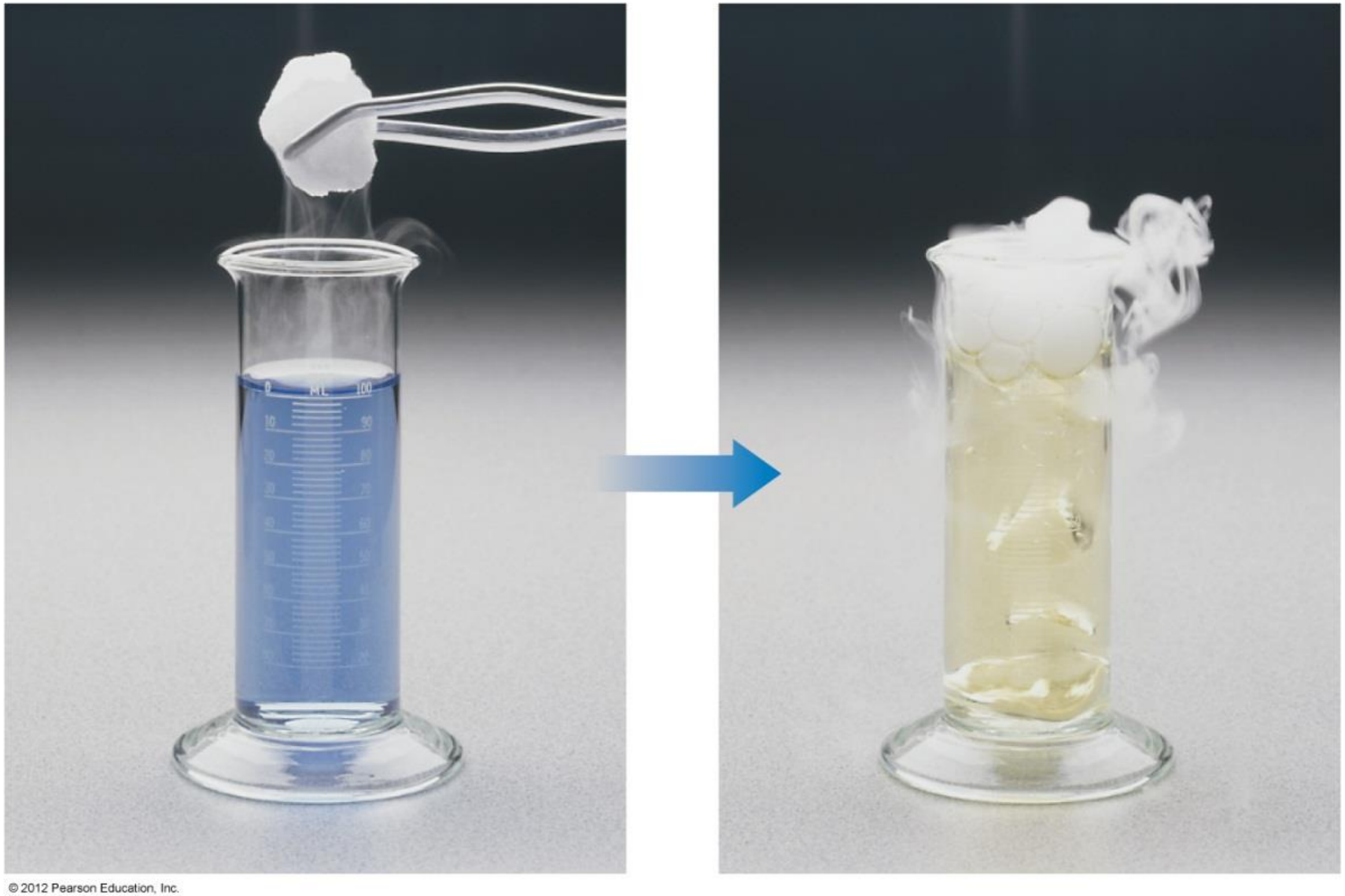

NiO is insoluble in water but reacts with $HNO_3$ to give a green solution of the salt $Ni(NO_3)_2$

$$NiO(s) + 2HNO_3(aq) \rightarrow Ni(NO_3)_2(aq) + H_2O(l)$$

# Nonmetals



- Nonmetals are dull（钝的）, brittle（易碎的）substances that are poor conductors of heat and electricity.
- They tend to **gain electrons** in reactions with metals to **acquire a noble-gas configuration**.




pH indicator in the solution

$$CO_2 + H_2O \rightarrow H_2CO_3 \text{ (acidic)}$$

- Substances containing only nonmetals are **molecular compounds**.
- Most nonmetal oxides are acidic.

# Metalloids


- Metalloids have some characteristics of metals and some of nonmetals.
- For instance, silicon looks shiny, but is brittle and a fairly poor conductor.

# Group Trends

# Alkali Metals (Group IA)



- **Alkali metals** are **soft**, metallic solids.
- The name comes from the Arabic word for ashes.

- They are usually found only in compounds in nature, not in their elemental forms.
- They have low densities and melting points.
- They also have low ionization energies.

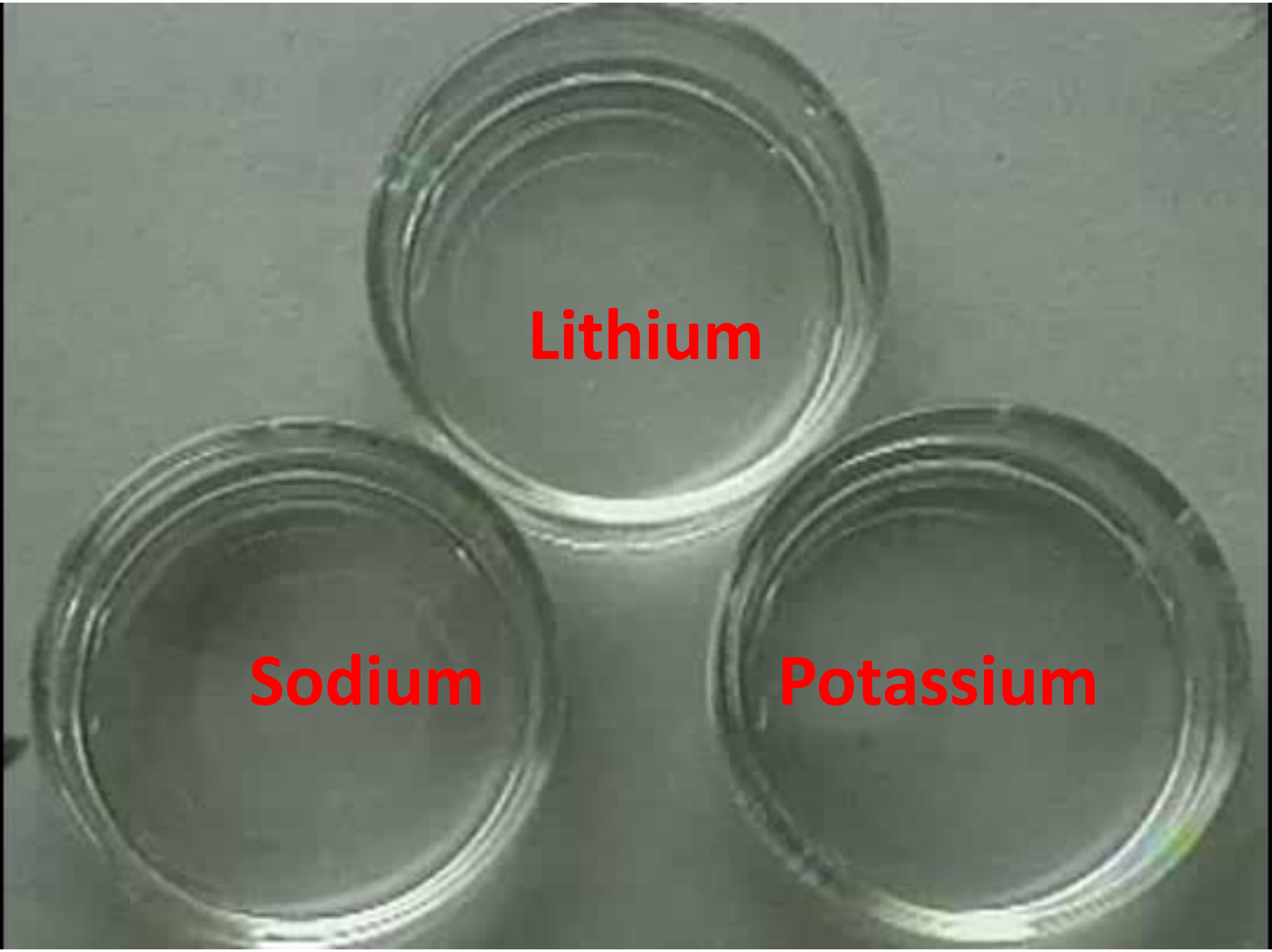
**TABLE 7.4 • Some Properties of the Alkali Metals**

| Element | Electron Configuration | Melting Point (°C) | Density ($g/cm^3$) | Atomic Radius (Å) | $I_1$ (kJ/mol) |
|---|---|---|---|---|---|
| Lithium | $[He]2s^1$ | 181 | 0.53 | 1.34 | 520 |
| Sodium | $[Ne]3s^1$ | 98 | 0.97 | 1.54 | 496 |
| Potassium | $[Ar]4s^1$ | 63 | 0.86 | 1.96 | 419 |
| Rubidium | $[Kr]5s^1$ | 39 | 1.53 | 2.11 | 403 |
| Cesium | $[Xe]6s^1$ | 28 | 1.88 | 2.25 | 376 |

Li Na K

Their reactions with water are famously exothermic.

$$2\ M(s) + 2\ H_2O(l) \rightarrow 2\ MOH(aq) + H_2(g)$$




Their reactions with water are famously exothermic.

- Most commonly, alkali metals react with oxygen to form oxides:

$$Li + O_2 \longrightarrow Li_2O\ (O^{2-}) \qquad O(-2)$$

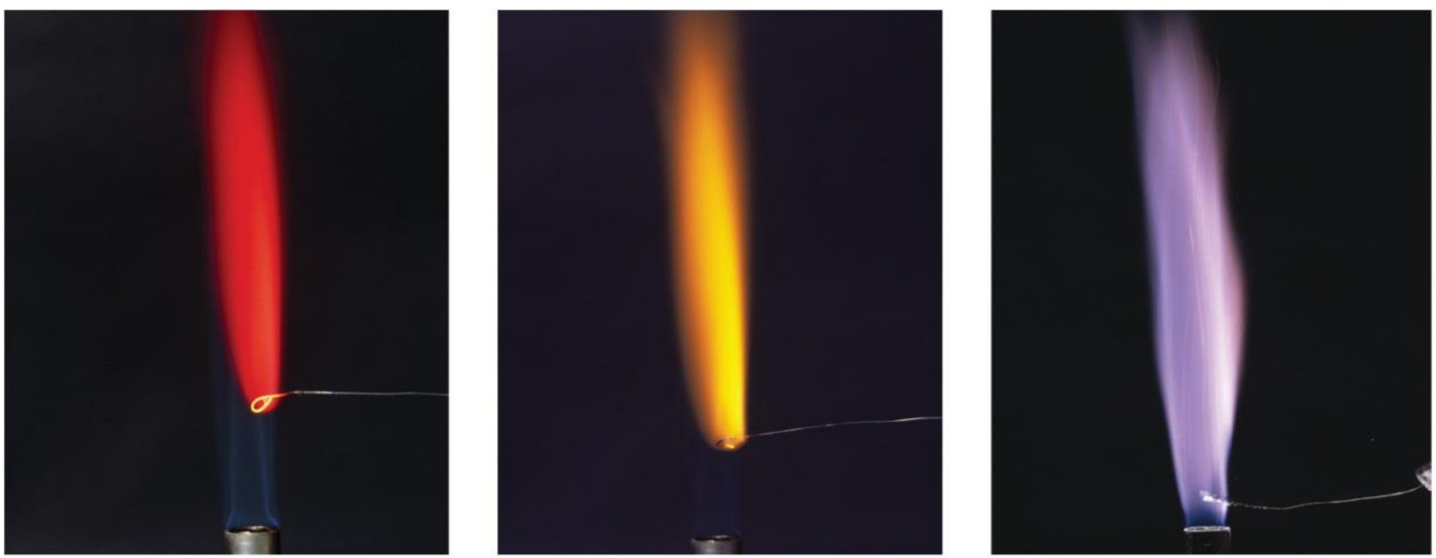
Alkali metals (except Li) can react with oxygen to form **peroxides**:

$$2Na + O_2 \longrightarrow Na_2O_2\ (O_2^{2-}) \qquad O(-1)$$

- K, Rb, and Cs also form superoxides:

$$K + O_2 \longrightarrow KO_2\ (O_2^{-}) \qquad O(-0.5)$$

- They produce bright colors when placed in a flame.





Li Na K

# Alkaline Earth Metals (Group 2A)

**Table 7.5 Some Properties of the Alkaline Earth Metals**

| Element | Electron Configuration | Melting Point (°C) | Density ($g/cm^3$) | Atomic Radius (Å) | $I_1$ (kJ/mol) |
|---|---|---|---|---|---|
| Beryllium | $[He]2s^2$ | 1287 | 1.85 | 0.96 | 899 |
| Magnesium | $[Ne]3s^2$ | 650 | 1.74 | 1.41 | 738 |
| Calcium | $[Ar]4s^2$ | 842 | 1.55 | 1.76 | 590 |
| Strontium | $[Kr]5s^2$ | 777 | 2.63 | 1.95 | 549 |
| Barium | $[Xe]6s^2$ | 727 | 3.51 | 2.15 | 503 |

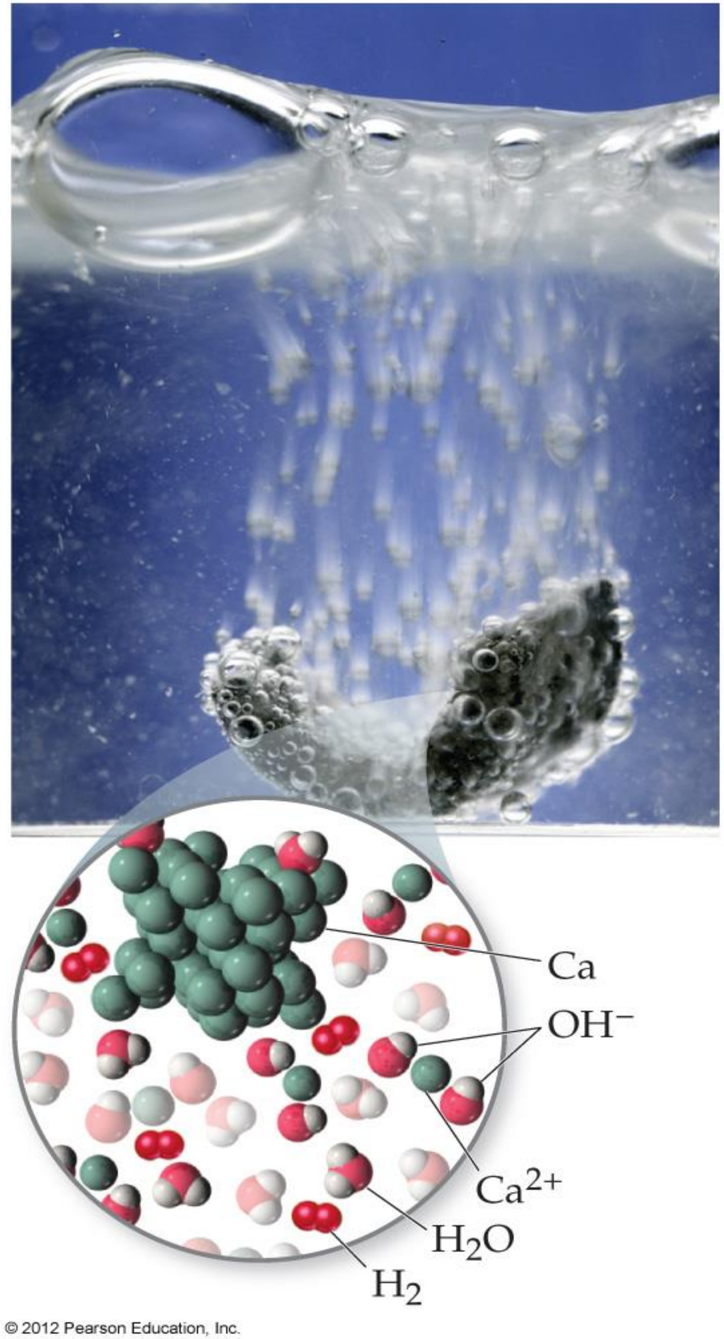
- Alkaline earth metals have higher densities & melting points than alkali metals.
- Their ionization energies are low, but not as low as those of alkali metals.

- Beryllium does **NOT** react with water.

- Magnesium reacts **ONLY** with steam.

- The other alkaline earth metals react **readily** with water.

- Reactivity tends to increase as you go down the group. Why?



# Chalcogens (Group 6A)

**Table 7.6 Some Properties of the Group 6A Elements**

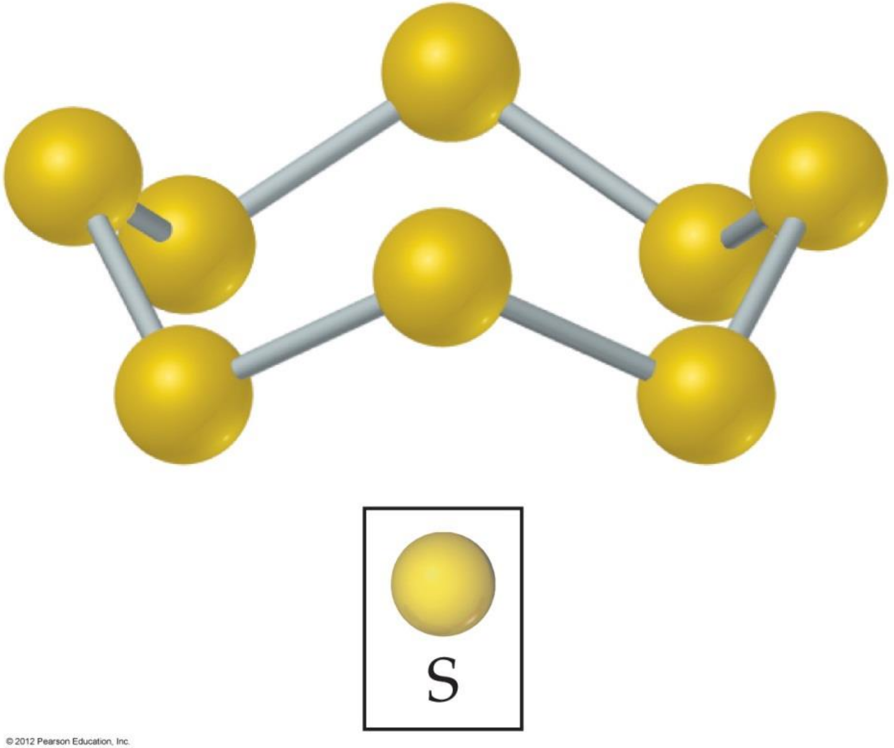
| Element | Electron Configuration | Melting Point (°C) | Density | Atomic Radius (Å) | $I_1$ (kJ/mol) |
|---|---|---|---|---|---|
| Oxygen | $[He]2s^22p^4$ | −218 | 1.43 g/L | 0.66 | 1314 |
| Sulfur | $[Ne]3s^23p^4$ | 115 | 1.96 g/cm$^3$ | 1.05 | 1000 |
| Selenium | $[Ar]3d^{10}4s^24p^4$ | 221 | 4.82 g/cm$^3$ | 1.20 | 941 |
| Tellurium | $[Kr]4d^{10}5s^25p^4$ | 450 | 6.24 g/cm$^3$ | 1.38 | 869 |
| Polonium | $[Xe]4f^{14}5d^{10}6s^26p^4$ | 254 | 9.20 g/cm$^3$ | 1.40 | 812 |

- Oxygen, sulfur & selenium are nonmetals.
- Tellurium is a metalloid.
- The radioactive polonium is a metal.

# Sulfur

- A weaker oxidizer than oxygen (the electron affinity of oxygen > sulfur).

- The most stable allotrope is $S_8$, a ringed molecule.



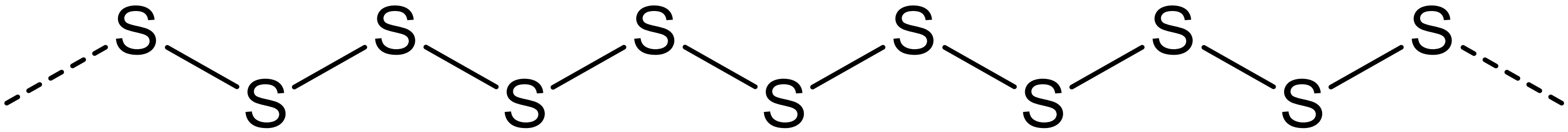
# Plastic Sulfur

113 $^{o}$C Melting Point

| | |
|---|---|
| 160 $^oC$ | $S_8$ breaks up, forms chains |
| 180 $^oC$ | Brown and Viscous |

| | |
|---|---|
| 200 $^{o}$C | Chains Shorten |
| 445 $^{o}$C | Boiling Point |


Plastic Sulfur

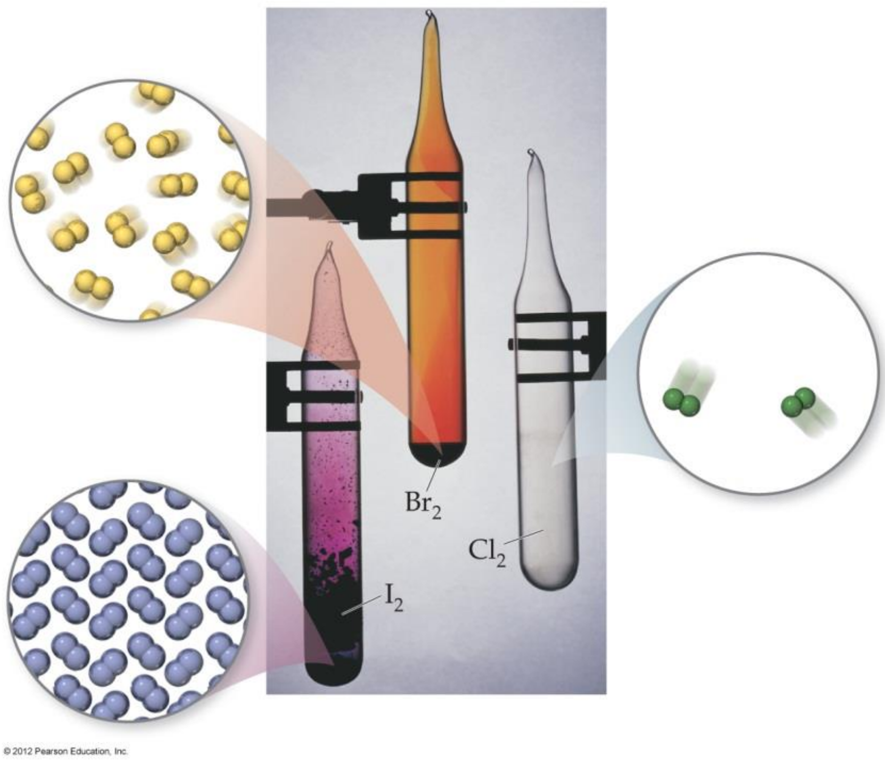


# Halogens (Group VIIA)

**Table 7.7 Some Properties of the Halogens**

| Element | Electron Configuration | Melting Point (°C) | Density | Atomic Radius (Å) | $I_1$ (kJ/mol) |
|---|---|---|---|---|---|
| Fluorine | $[He]2s^22p^5$ | −220 | 1.69 g/L | 0.57 | 1681 |
| Chlorine | $[Ne]3s^23p^5$ | −102 | 3.12 g/L | 1.02 | 1251 |
| Bromine | $[Ar]4s^23d^{10}4p^5$ | −7.3 | 3.12 g/cm$^3$ | 1.20 | 1140 |
| Iodine | $[Kr]5s^24d^{10}5p^5$ | 114 | 4.94 g/cm$^3$ | 1.39 | 1008 |

- The **halogens** are prototypical nonmetals.
- The name comes from the Greek words *halos* and *gennao*: "salt formers".




- They have **large, negative electron affinities**. Thus, they tend to oxidize other elements easily.

- They react directly with metals to form metal halides.

- Chlorine is added to water supplies to serve as a disinfectant（消毒剂） HOCl(aq):

$Cl_2(g) + H_2O(l) \rightarrow HCl(aq) + $ **HOCl**(aq))

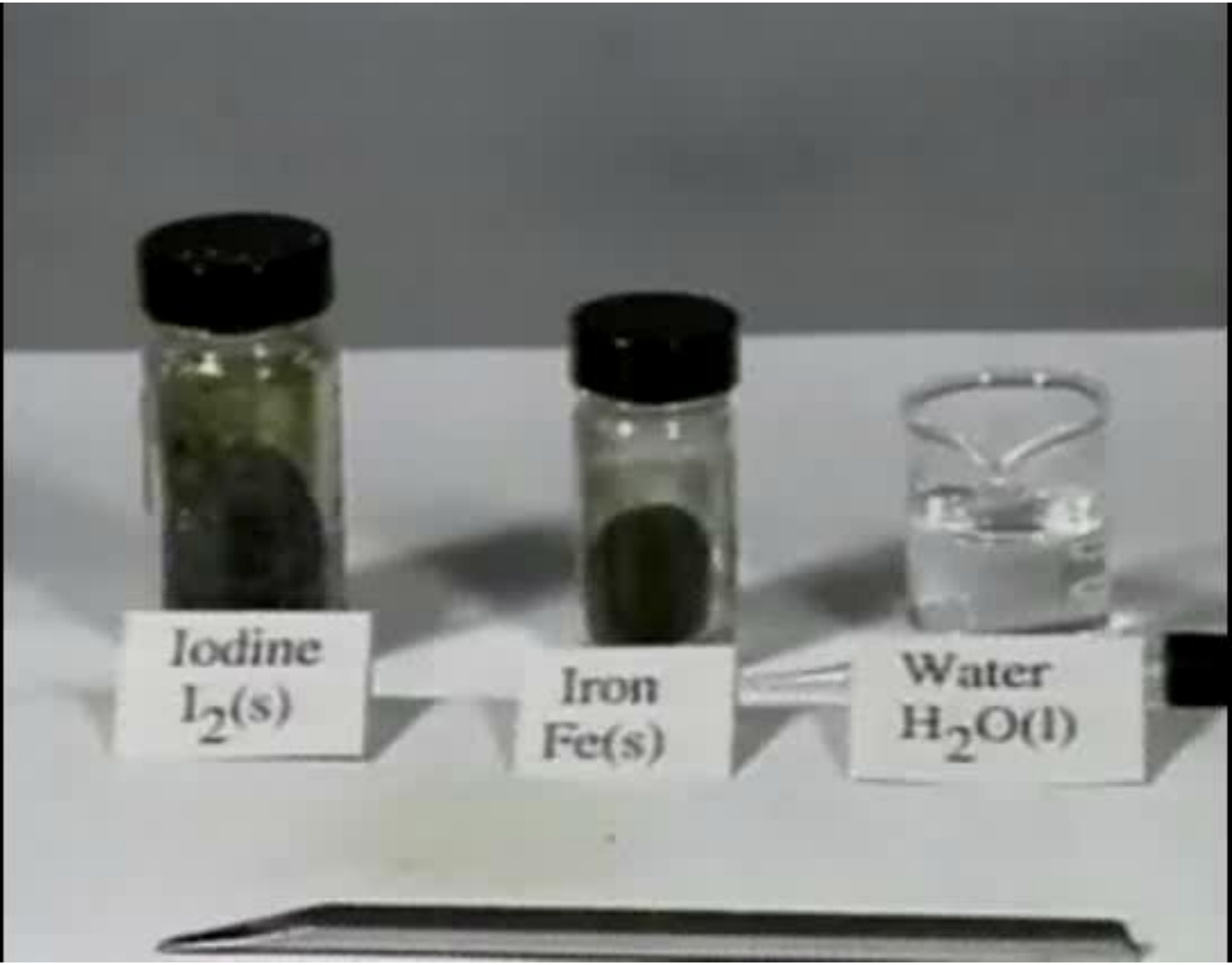
# Chlorine Gas Reacts with Sodium Metal

$$Cl_2(g) + 2\ Na(s) \rightarrow 2\ NaCl(s)$$

# Chlorine Gas Reacts with Iron Metal

$$3\ Cl_2(g) + 2\ Fe(s) \rightarrow 2\ FeCl_3(s)$$

# Iodine Solid Reacts with Iron Metal




$$I_2(s) + Fe(s) \rightarrow FeI_2(s)$$

# Noble Gases (Group VIIIA)

| Element | Electron Configuration | Boiling Point (K) | Density (g/L) | Atomic Radius* (Å) | $I_1$ (kJ/mol) |
|---|---|---|---|---|---|
| Helium | $1s^2$ | 4.2 | 0.18 | 0.28 | 2372 |
| Neon | $[He]2s^22p^6$ | 27.1 | 0.90 | 0.58 | 2081 |
| Argon | $[Ne]3s^23p^6$ | 87.3 | 1.78 | 1.06 | 1521 |
| Krypton | $[Ar]4s^23d^{10}4p^6$ | 120 | 3.75 | 1.16 | 1351 |
| Xenon | $[Kr]5s^24d^{10}5p^6$ | 165 | 5.90 | 1.40 | 1170 |
| Radon | $[Xe]6s^24f^{14}5d^{10}6p^6$ | 211 | 9.73 | 1.50 | 1037 |

*Only the heaviest of the noble-gas elements form chemical compounds. Thus, the atomic radii for the lighter noble gas elements are estimated values.

- The **noble gases** (inert（惰性） gases) have very large ionization energies.
- Their electron affinities are positive.
- Therefore, they are relatively unreactive.
- They are found as monatomic gases.
- Synthesized $XeF_2$, $XeF_4$, $XeF_6$, $KrF_2$ & HArF since 1962

Describe a general relationship between trends in metallic character and trends in ionization energy.

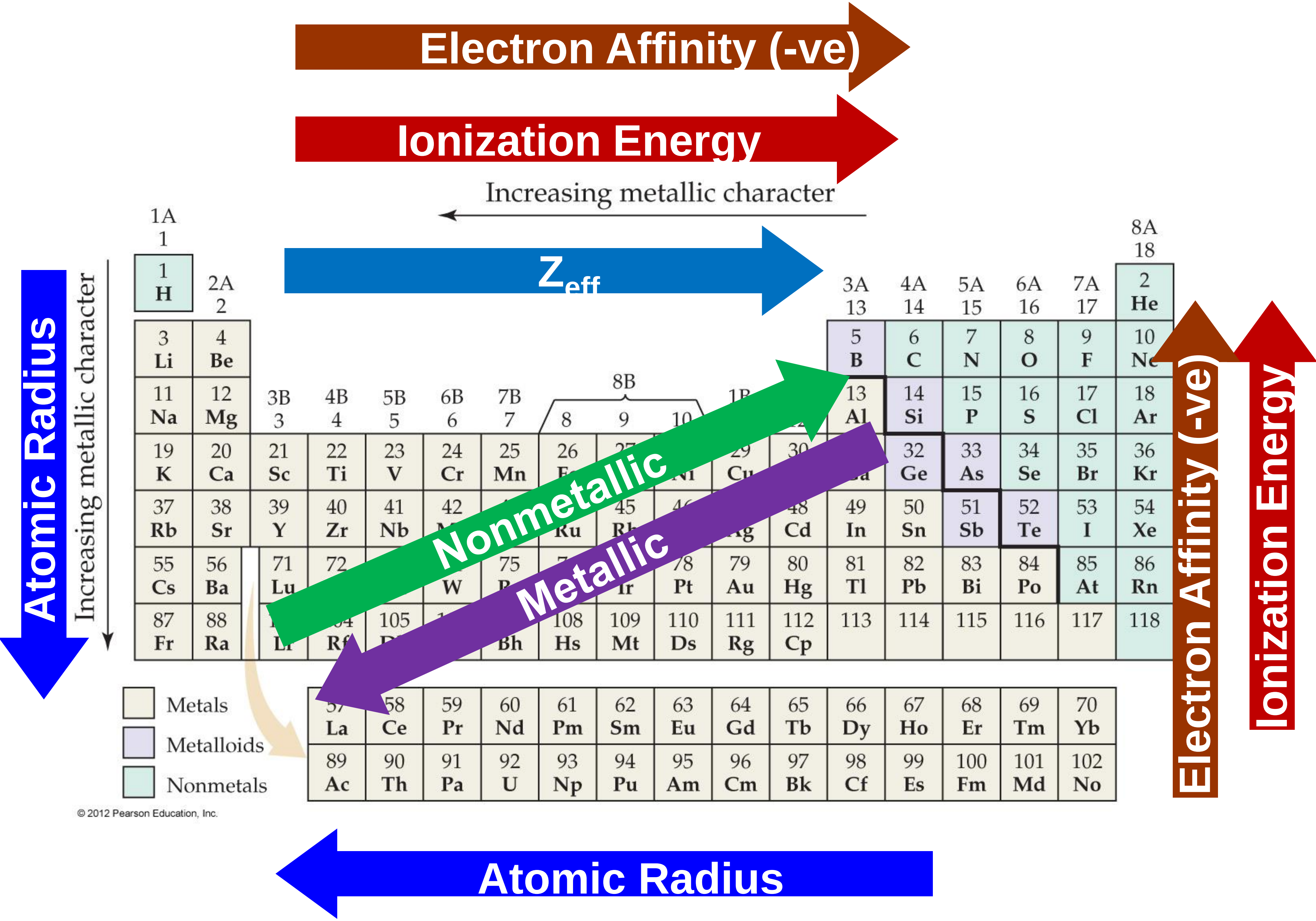
A. There is no correlation between ionization energy and metallic character.
B. Increasing ionization energy correlates with decreasing metallic character.
C. Increasing ionization energy correlates with increasing metallic character.
D. Decreasing ionization energy correlates with decreasing metallic character.

Most metal oxides form ________ solutions when dissolved in water.

a. acidic
b. basic
c. neutral
d. amphoteric

Most nonmetal oxides form ________ solutions when dissolved in water.

a. acidic
b. basic
c. neutral
d. amphoteric


Electron Affinity (-ve)
Ionization Energy
Increasing metallic character
Zeff
Atomic Radius
Increasing metallic character
Nonmetallic
Metallic
Electron Affinity (-ve)
Ionization Energy
Metals
Metalloids
Nonmetals
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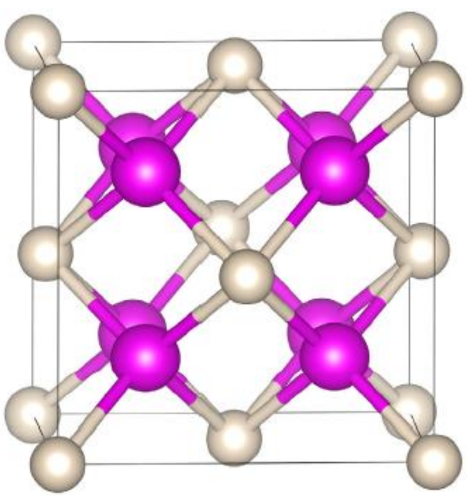
Atomic Radius

# A stable compound of helium and sodium at high pressure

**Extra Info:**

Xiao Dong[1,2,3], Artem R. Oganov[3,4,5,6*], Alexander F. Goncharov[7,8], Elissaios Stavrou[7,9], Sergey Lobanov[7,10], Gabriele Saleh[5], Guang-Rui Qian[3], Qiang Zhu[3], Carlo Gatti[11], Volker L. Deringer[12], Richard Dronskowski[12], Xiang-Feng Zhou[1,3*], Vitali B. Prakapenka[13], Zuzana Konôpková[14], Ivan A. Popov[15,16], Alexander I. Boldyrev[15] and Hui-Tian Wang[1,17*]

**Helium is generally understood to be chemically inert and this is due to its extremely stable closed-shell electronic configuration, zero electron affinity and an unsurpassed ionization potential. It is not known to form thermodynamically stable compounds, except a few inclusion compounds. Here, using the *ab initio* evolutionary algorithm USPEX and subsequent high-pressure synthesis in a diamond anvil cell, we report the discovery of a thermodynamically stable compound of helium and sodium, $Na_2He$, which has a fluorite-type structure and is stable at pressures >113 GPa. We show that the presence of He atoms causes strong electron localization and makes this material insulating. This phase is an electride, with electron pairs localized in interstices, forming eight-centre two-electron bonds within empty $Na_8$ cubes. We also predict the existence of $Na_2HeO$ with a similar structure at pressures above 15 GPa.**




X-ray crystal structure of $Na_2He$ at 300 GPa



*Nature Chem*, **2017**, 440.

Noble-Gas Chemistry Very Important Paper

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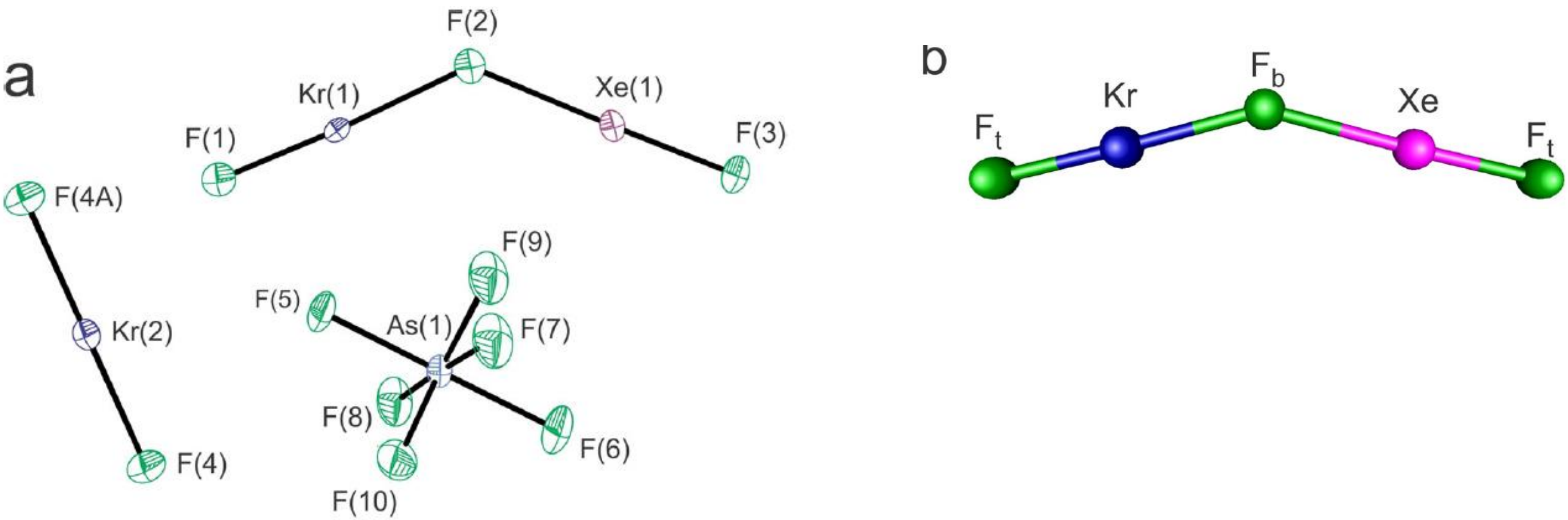
# Syntheses and Characterizations of the Mixed Noble-Gas Compounds, $[FKr^{II}FXe^{II}F][AsF_6]\cdot 0.5Kr^{II}F_2\cdot 2HF$, $([Kr^{II}{}_2F_3][AsF_6])_2\cdot Xe^{IV}F_4$, and $Xe^{IV}F_4\cdot Kr^{II}F_2$

**Extra Info:**

*Mark R. Bortolus, Hélène P. A. Mercier, Brianna Nguyen, and Gary J. Schrobilgen**



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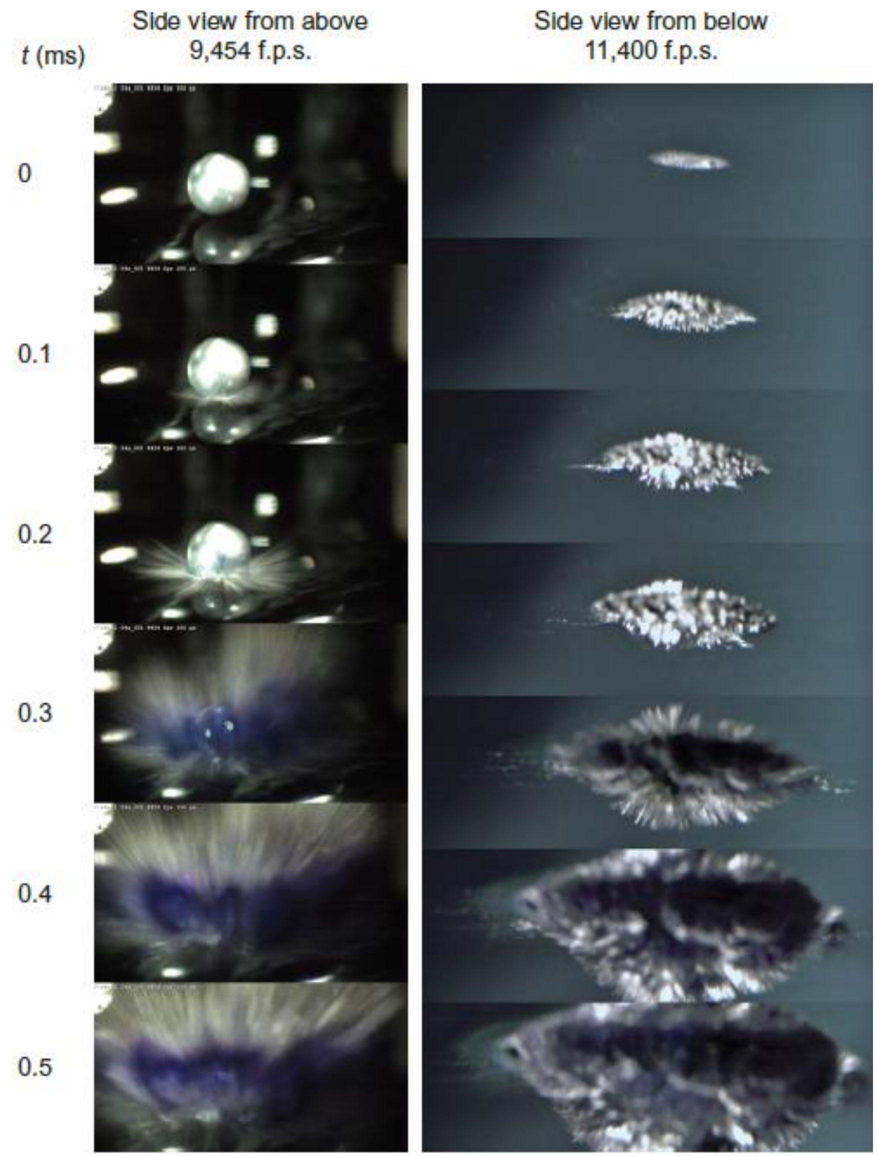
PUBLISHED ONLINE: 26 JANUARY 2015 | DOI: 10.1038/NCHEM.2161
nature chemistry

# Extra Info:

## Coulomb explosion during the early stages of the reaction of alkali metals with water

Na




High-speed camera

Mason Nature Chem, 2015, 250.

# Key Summary

**Development of Periodic Table**

**Periodic Trends**:
Effective Nuclear Charge: Shielding
Sizes of Atoms & Ions: (non)bonding atomic radius;
Ionization Energy
Electron Affinity

**Properties of Metal, Nonmetals, and Metalloids**

# Thank You for Your Attention!
# Any Questions?