

Chemistry, The Central Science, 10th edition

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Chapter 7

Periodic Properties of the Elements

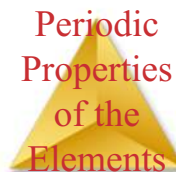
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Periodic
Properties
of the
Elements










Development of Periodic Table

- Elements in the same group generally have similar chemical properties.
- Properties are not identical, however.



Development of Periodic Table

H																	He
Li	Be											B	C	N	O	F	Ne
Na	Mg											Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba	La	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra	Ac	Rf	Db	Sg	Bh	Hs	Mt									
			Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	
			Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr	

	Ancient Times		1735–1843		1894–1918		
	Middle Ages–1700		1843–1886		1923–1961		1965–

Dmitri Mendeleev
and Lothar
Meyer
independently
came to the
same conclusion
about how
elements should
be grouped.

Development of Periodic Table

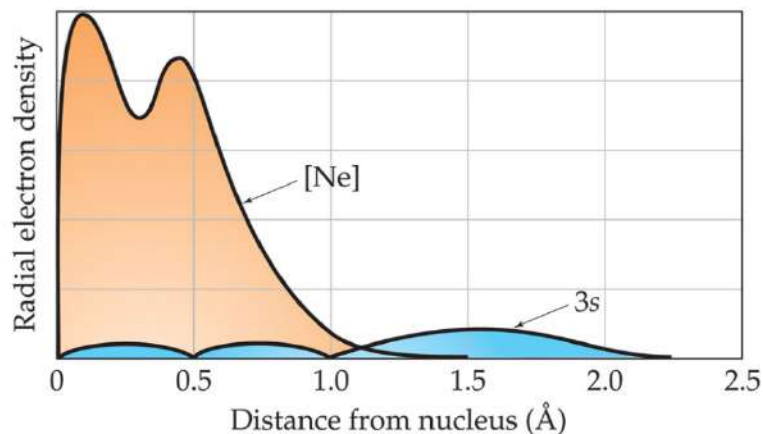
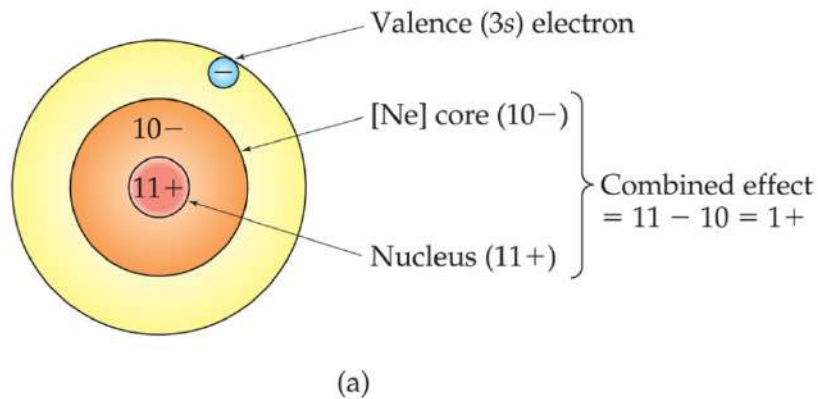
Property	Mendeleev's Predictions for Eka-Silicon (made in 1871)	Observed Properties of Germanium (discovered in 1886)
Atomic weight	72	72.59
Density (g/cm ³)	5.5	5.35
Specific heat (J/g-k)	0.305	0.309
Melting point (°C)	High	947
Color	Dark gray	Grayish white
Formula of oxide	XO ₂	GeO ₂
Density of oxide (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, for instance, predicted the discovery of germanium (which he called eka-silicon) as an element with an atomic weight between that of zinc and arsenic, but with chemical properties similar to those of silicon.

Periodic Trends

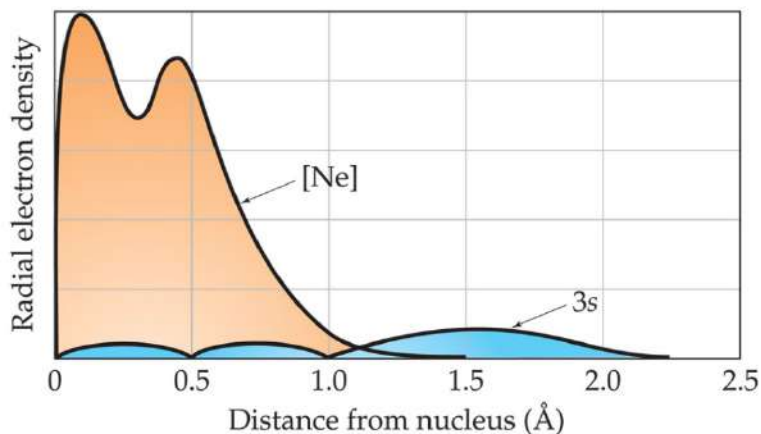
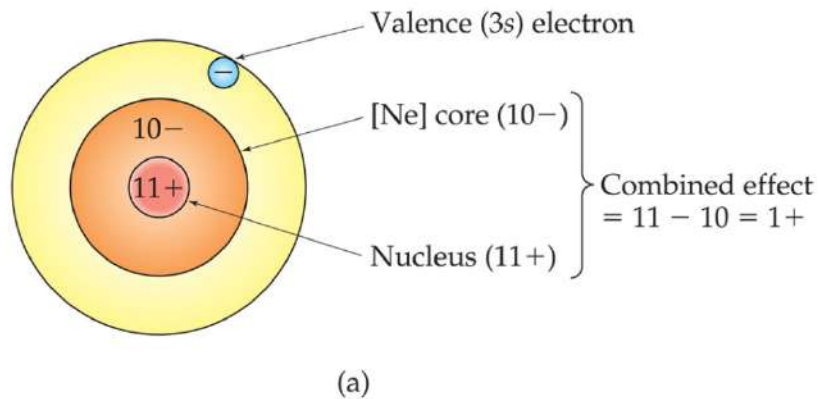
- In this chapter, we will rationalize observed trends in
 - Sizes of atoms and ions.
 - Ionization energy.
 - Electron affinity.

Effective Nuclear Charge



- In a many-electron atom, electrons are both attracted to the nucleus and repelled by other electrons.
- The nuclear charge that an electron experiences depends on both factors.

Effective Nuclear Charge



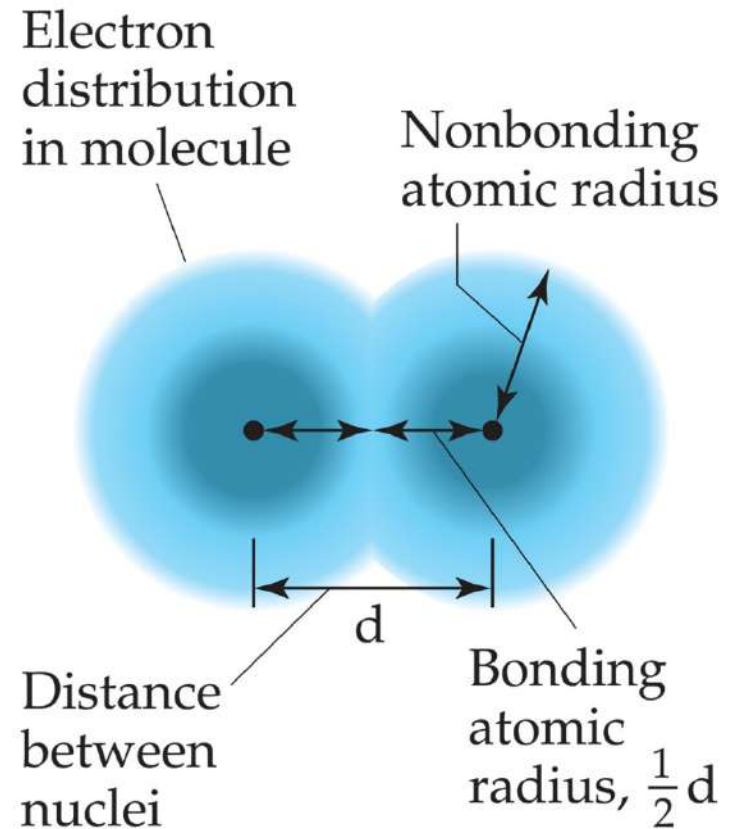
The effective nuclear charge, Z_{eff} , is found this way:

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

where Z is the atomic number and S is a screening constant, usually close to the number of inner electrons.

Sizes of Atoms

The bonding atomic radius is defined as one-half of the distance between covalently bonded nuclei.



Sizes of Atoms

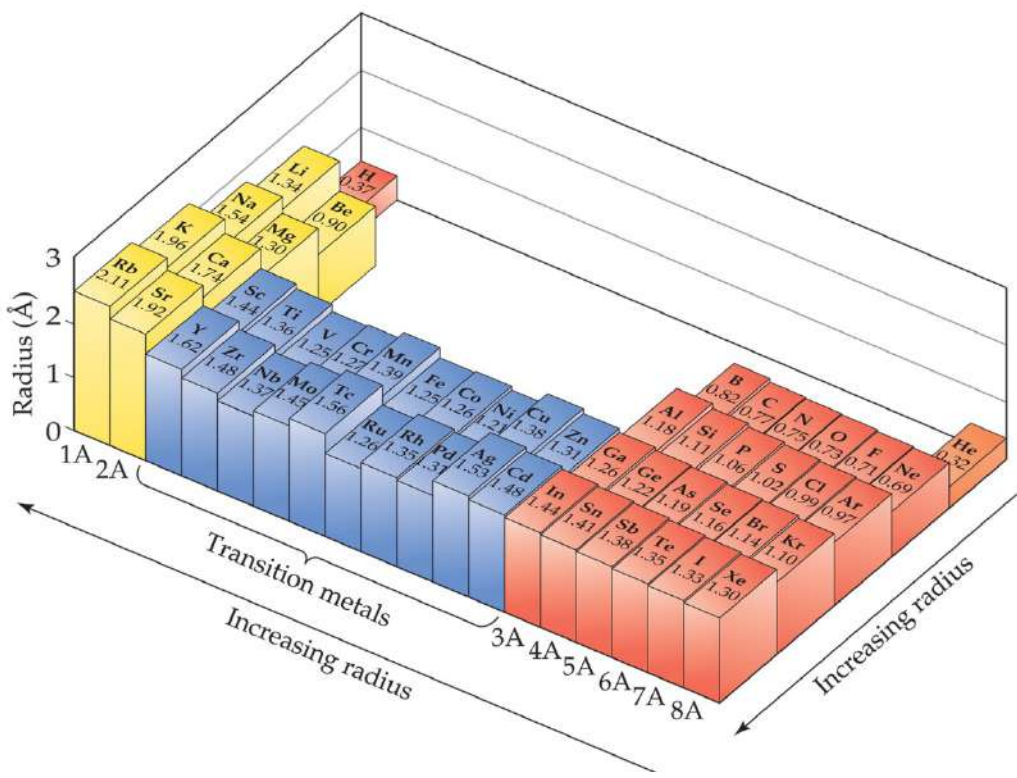
Bonding atomic radius tends to...

...decrease from left to right across a row

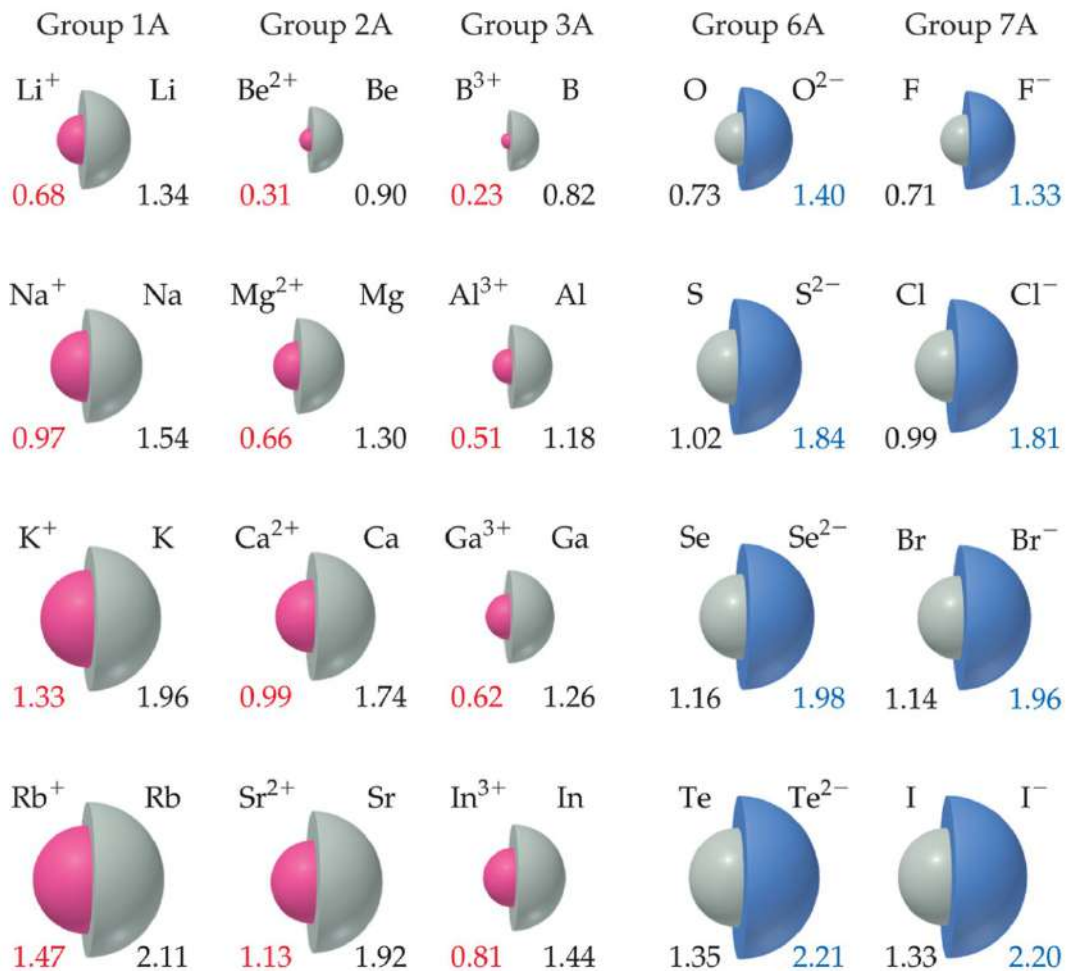
due to increasing Z_{eff} .

...increase from top to bottom of a column

due to increasing value of n



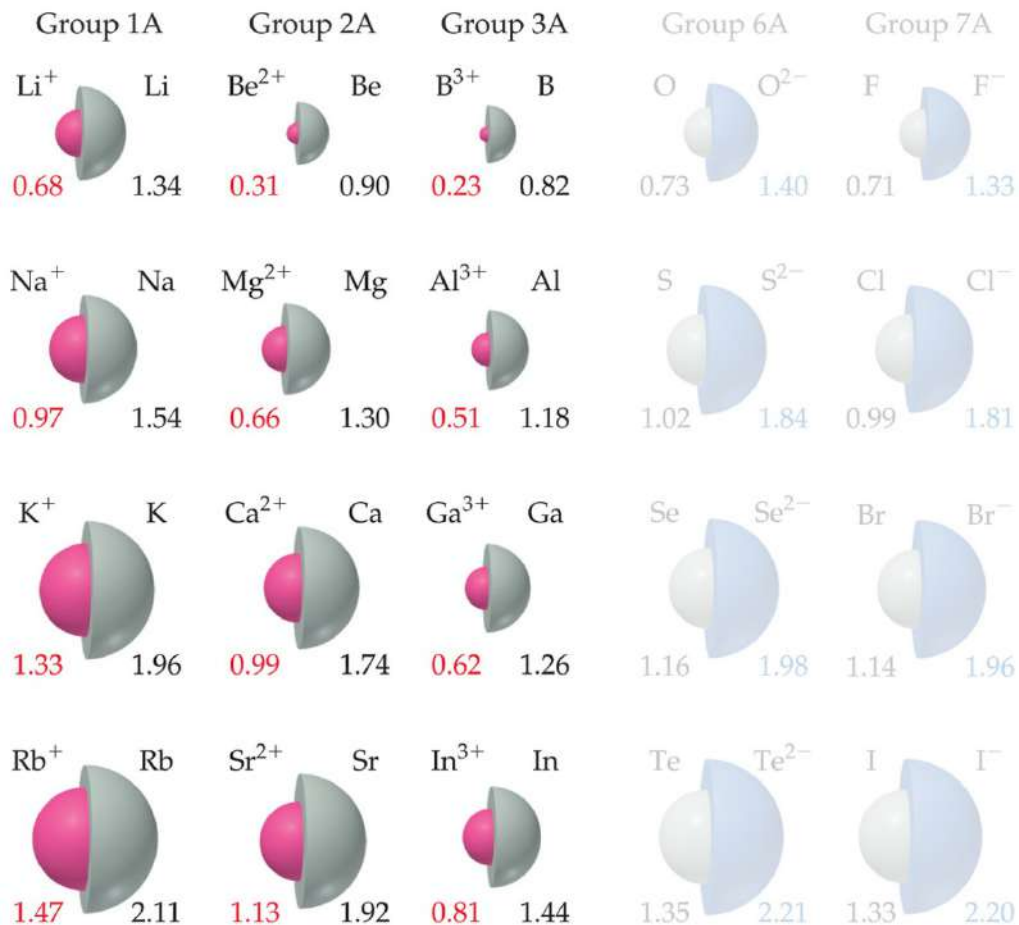
Sizes of Ions



- Ionic size depends upon:

- Nuclear charge.
- Number of electrons.
- Orbitals in which electrons reside.

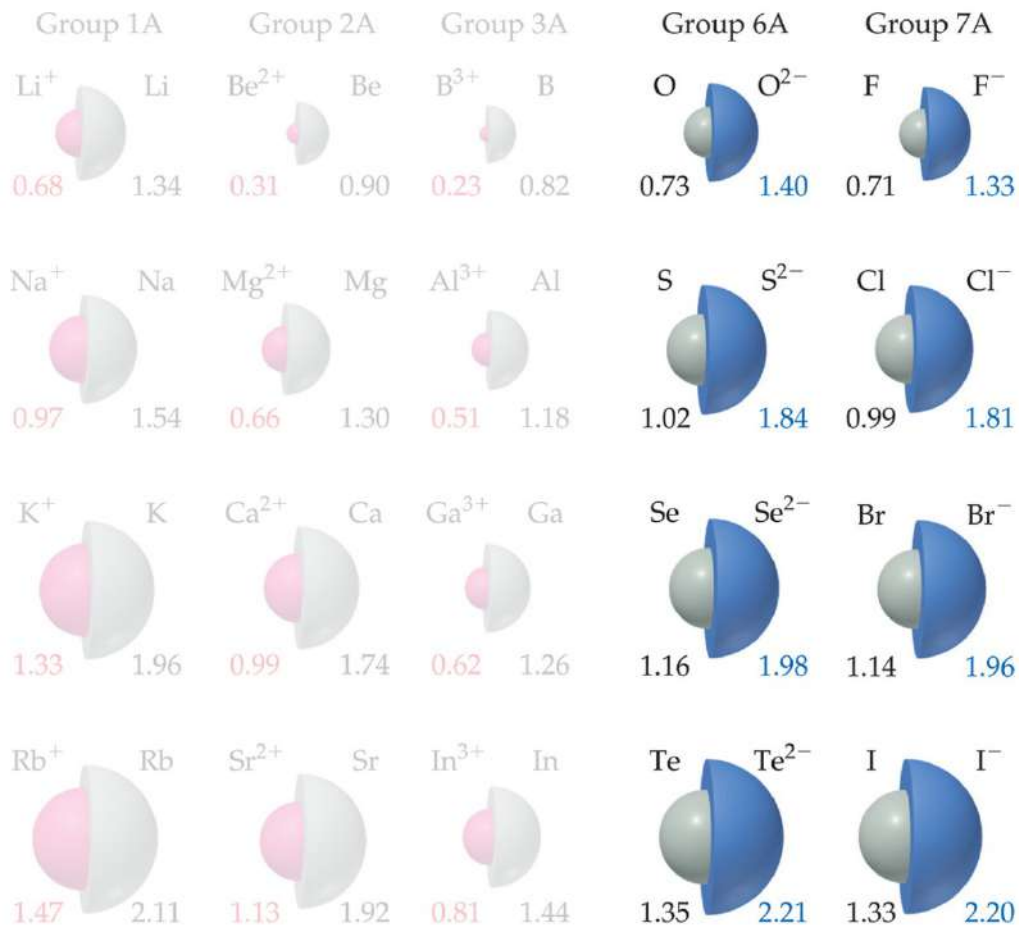
Sizes of Ions



- Cations are smaller than their parent atoms.

- The outermost electron is removed and repulsions are reduced.

Sizes of Ions

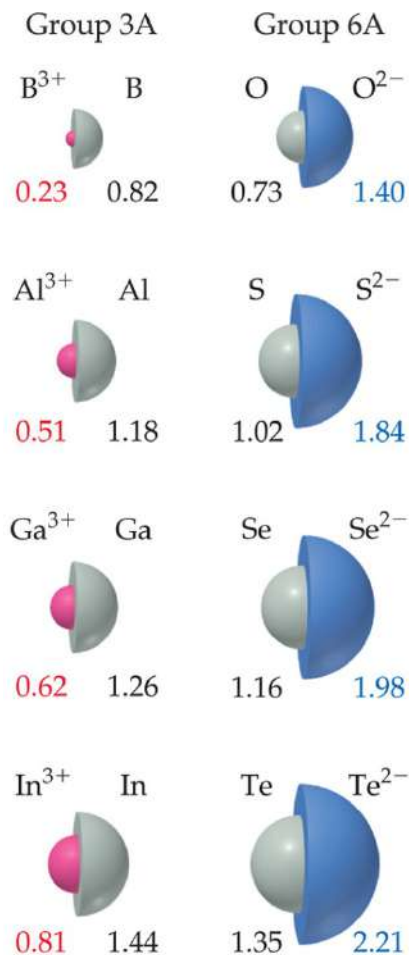


- Anions are larger than their parent atoms.

➤ Electrons are added and repulsions are increased.

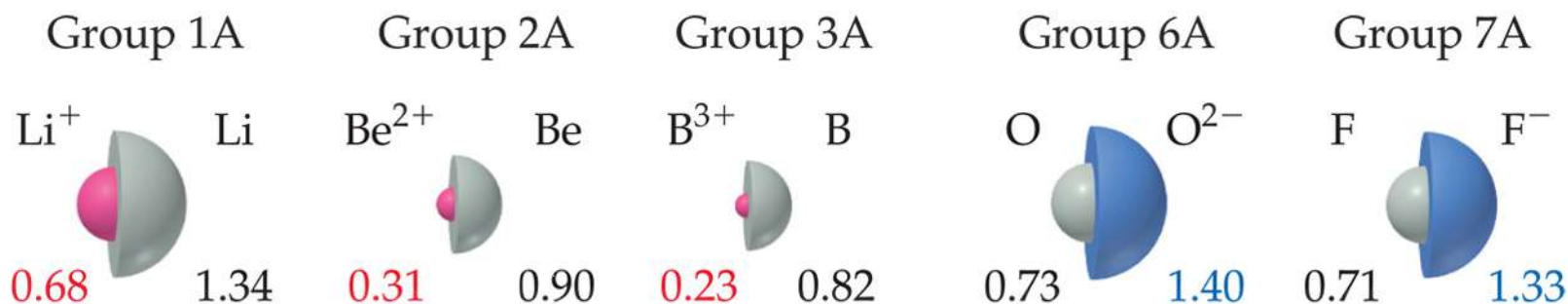
Sizes of Ions

- Ions increase in size as you go down a column.
 - Due to increasing value of n .



Sizes of Ions

- In an **isoelectronic series**, ions have the same number of electrons.
- Ionic size decreases with an increasing nuclear charge.



Ionization Energy

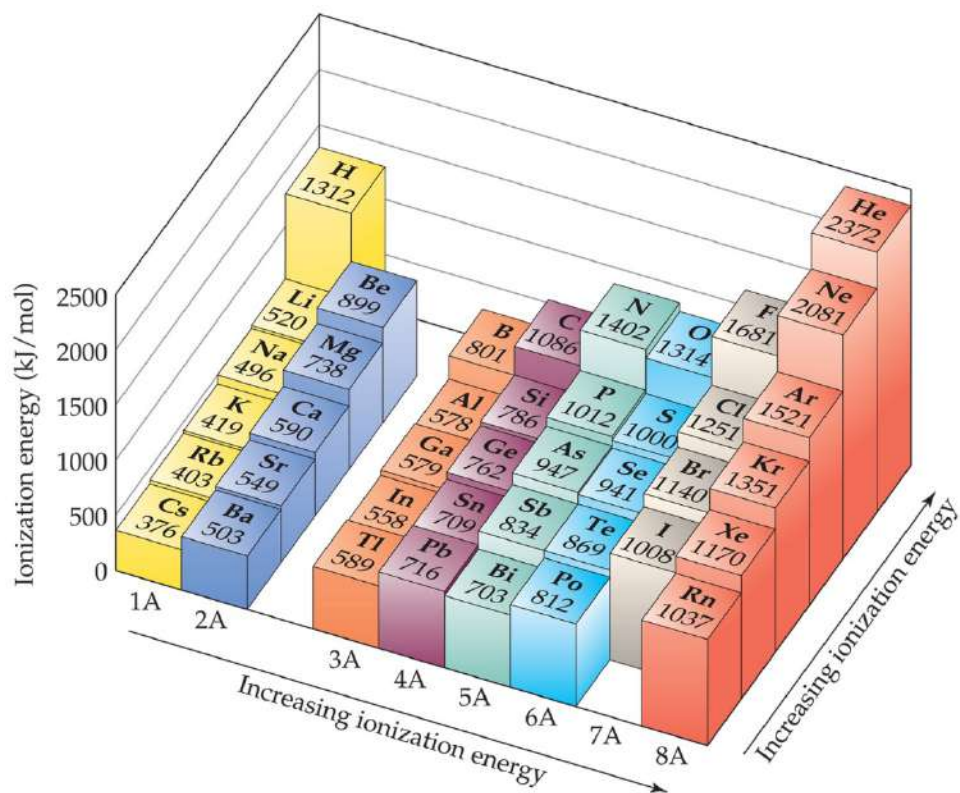
- Amount of energy required to remove an electron from the ground state of a gaseous atom or ion.
 - First ionization energy is that energy required to remove first electron.
 - Second ionization energy is that energy required to remove second electron, etc.

Ionization Energy

- It requires more energy to remove each successive electron.
- When all valence electrons have been removed, the ionization energy takes a quantum leap.

Element	I_1	I_2	I_3	I_4	I_5	I_6	I_7
Na	495	4562					
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

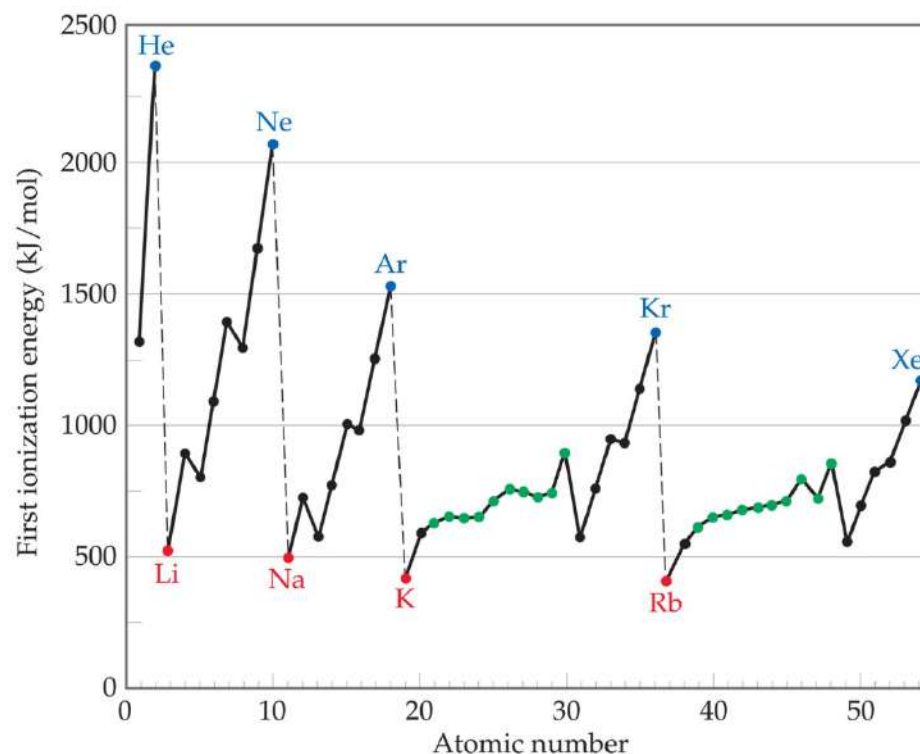
Trends in First Ionization Energies



- As one goes down a column, less energy is required to remove the first electron.
 - For atoms in the same group, Z_{eff} is essentially the same, but the valence electrons are farther from the nucleus.

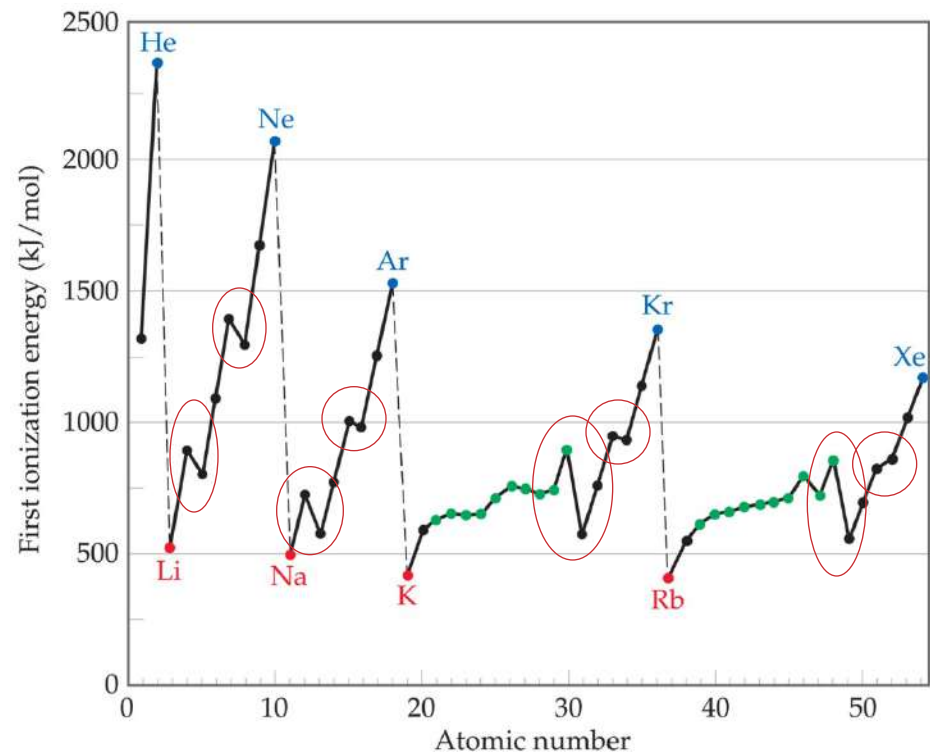
Trends in First Ionization Energies

- Generally, as one goes across a row, it gets harder to remove an electron.
 - As you go from left to right, Z_{eff} increases.



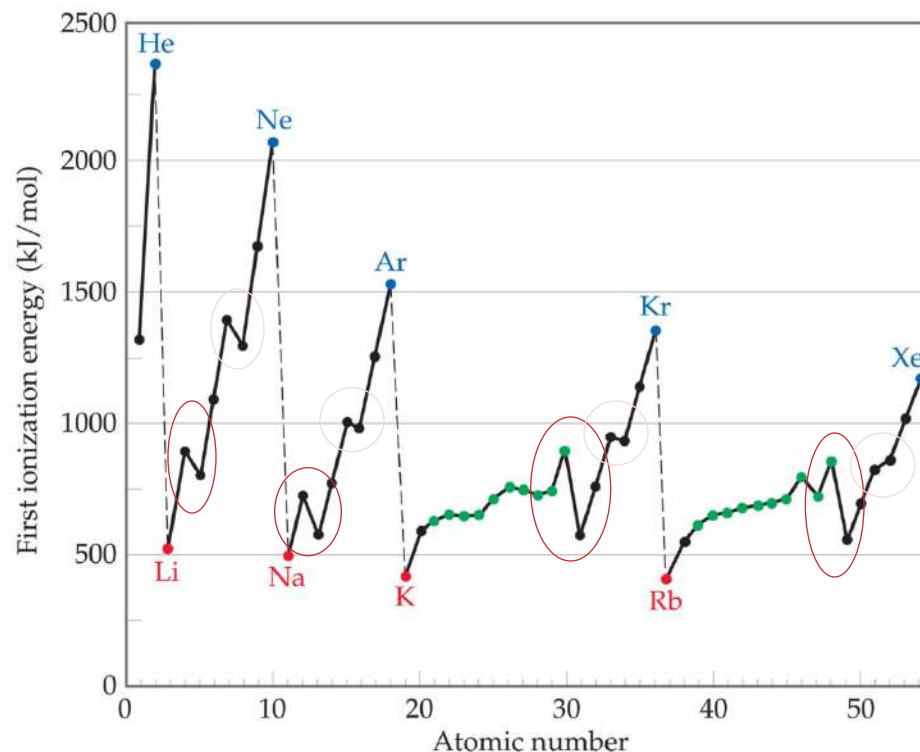
Trends in First Ionization Energies

However, there are two apparent discontinuities in this trend.



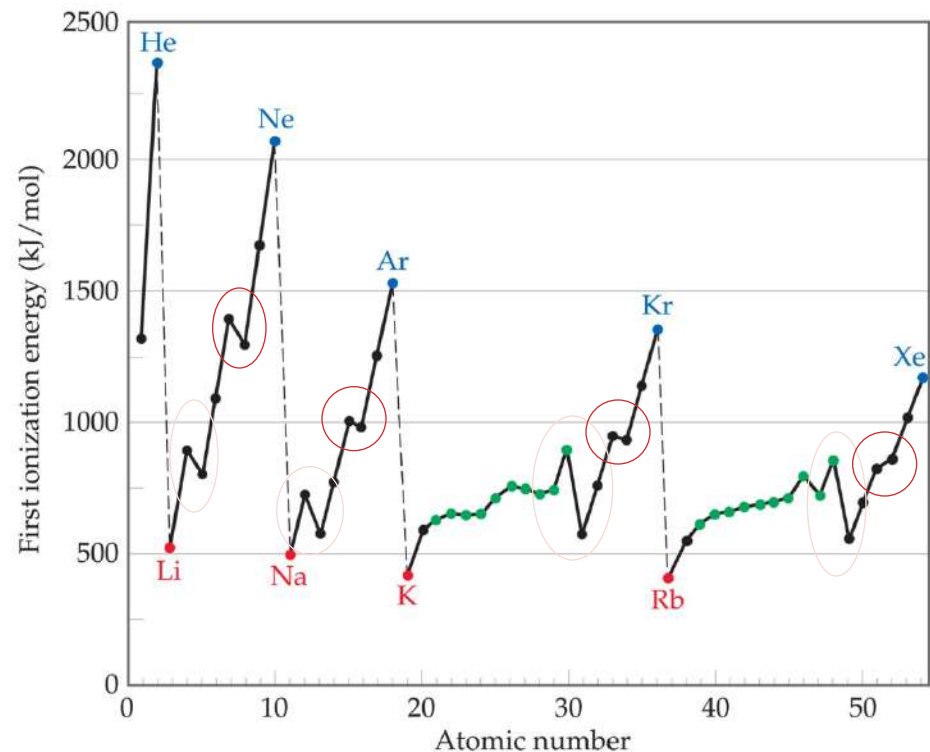
Trends in First Ionization Energies

- The first occurs between Groups IIA and IIIA.
- Electron removed from p -orbital rather than s -orbital
 - Electron farther from nucleus
 - Small amount of repulsion by s electrons.



Trends in First Ionization Energies

- The second occurs between Groups VA and VIA.
 - Electron removed comes from doubly occupied orbital.
 - Repulsion from other electron in orbital helps in its removal.



Electron Affinity

Energy change accompanying addition of electron to gaseous atom:



Trends in Electron Affinity

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
1A	2A	3A	4A	5A	6A	7A	8A	

In general, electron affinity becomes more exothermic as you go from left to right across a row.

Trends in Electron Affinity

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
1A	2A	3A	4A	5A	6A	7A	8A

There are again, however, two discontinuities in this trend.

Trends in Electron Affinity

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
1A	2A	3A	4A	5A	6A	7A	8A

- The first occurs between Groups IA and IIA.
 - Added electron must go in *p*-orbital, not *s*-orbital.
 - Electron is farther from nucleus and feels repulsion from *s*-electrons.

Trends in Electron Affinity

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
1A	2A	3A	4A	5A	6A	7A	8A

- The second occurs between Groups IVA and VA.
 - Group VA has no empty orbitals.
 - Extra electron must go into occupied orbital, creating repulsion.

Properties of Metal, Nonmetals, and Metalloids

← Increasing metallic character →

Increasing metallic character ↓

1A 1	2A 2											3A 13	4A 14	5A 15	6A 16	7A 17	8A 18	
1 H												5 B	6 C	7 N	8 O	9 F	10 Ne	
3 Li	4 Be						8B 8 9 10			1B 11	2B 12	13 Al	14 Si	15 P	16 S	17 Cl	18 Ar	
11 Na	12 Mg	3B 3	4B 4	5B 5	6B 6	7B 7	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr	
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr	
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe	
55 Cs	56 Ba		71 Lu	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra	103 Lr	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110	111	112	113	114	115	116			

Metals	57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb
Metalloids	89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No
Nonmetals														

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

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 versus Nonmetals

- Metals tend to form cations.
- Nonmetals tend to form anions.

1A	2A	Transition metals										3A	4A	5A	6A	7A	8A	
H ⁺																	H ⁻	N O B L E G A S E S
Li ⁺												Al ³⁺			N ³⁻	O ²⁻	F ⁻	
Na ⁺	Mg ²⁺				Cr ³⁺	Mn ²⁺	Fe ²⁺ Fe ³⁺	Co ²⁺	Ni ²⁺	Cu ⁺ Cu ²⁺	Zn ²⁺				P ³⁻	S ²⁻	Cl ⁻	
K ⁺	Ca ²⁺															Se ²⁻	Br ⁻	
Rb ⁺	Sr ²⁺									Ag ⁺	Cd ²⁺		Sn ²⁺		Te ²⁻	I ⁻		
Cs ⁺	Ba ²⁺								Pt ²⁺	Au ⁺ Au ³⁺	Hg ₂ ²⁺ Hg ²⁺		Pb ²⁺	Bi ³⁺				

Metals



Tend to be lustrous, malleable, ductile, and good conductors of heat and electricity.

Metals

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



Nonmetals



- Dull, brittle substances that are poor conductors of heat and electricity.
- Tend to gain electrons in reactions with metals to acquire noble gas configuration.

Nonmetals

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



Metalloids



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

Group Trends

Alkali Metals

- Soft, metallic solids.
- Name comes from Arabic word for ashes.



Alkali Metals

- Found only as compounds in nature.
- Have low densities and melting points.
- Also have low ionization energies.

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

Alkali Metals



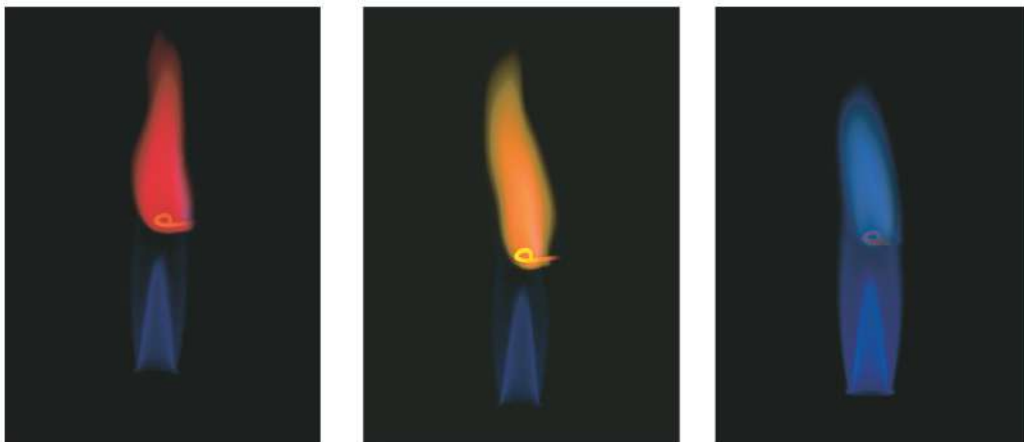
Their reactions with water are famously exothermic.

Alkali Metals

- Alkali metals (except Li) react with oxygen to form peroxides.
- K, Rb, and Cs also form superoxides:



- Produce bright colors when placed in flame.



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	0.90	899
Magnesium	[Ne]3s ²	650	1.74	1.30	738
Calcium	[Ar]4s ²	842	1.55	1.74	590
Strontium	[Kr]5s ²	777	2.63	1.92	549
Barium	[Xe]6s ²	727	3.51	1.98	503

- Have higher densities and melting points than alkali metals.
- Have low ionization energies, but not as low as alkali metals.

Alkaline Earth Metals

- Be does not react with water, Mg reacts only with steam, but others react readily with water.
- Reactivity tends to increase as go down group.

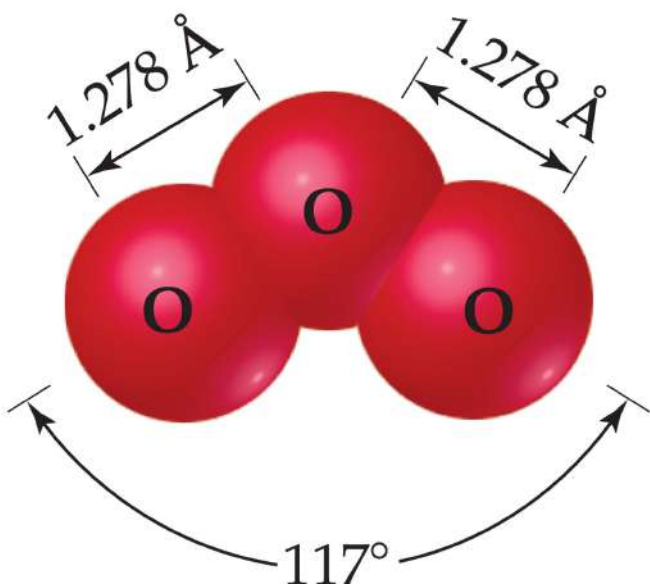


Group 6A

Element	Electron Configuration	Melting Point (°C)	Density	Atomic Radius (Å)	I_1 (kJ/mol)
Oxygen	[He]2s ² 2p ⁴	-218	1.43 g/L	0.73	1314
Sulfur	[Ne]3s ² 3p ⁴	15	1.96 g/cm ³	1.02	1000
Selenium	[Ar]3d ¹⁰ 4s ² 4p ⁴	221	4.82 g/cm ³	1.16	941
Tellurium	[Kr]4d ¹⁰ 5s ² 5p ⁴	450	6.24 g/cm ³	1.35	869
Polonium	[Xe]4f ¹⁴ 5d ¹⁰ 6s ² 6p ⁴	254	9.20 g/cm ³	—	812

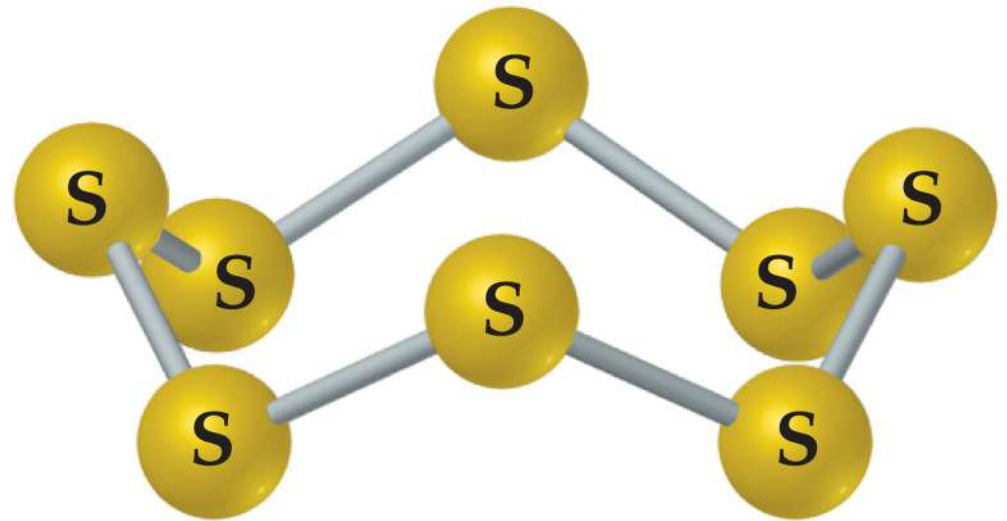
- Oxygen, sulfur, and selenium are nonmetals.
- Tellurium is a metalloid.
- The radioactive polonium is a metal.

Oxygen



- Two allotropes:
 - O_2
 - O_3 , ozone
- Three anions:
 - O^{2-} , oxide
 - O_2^{2-} , peroxide
 - O_2^{1-} , superoxide
- Tends to take electrons from other elements (oxidation)

Sulfur



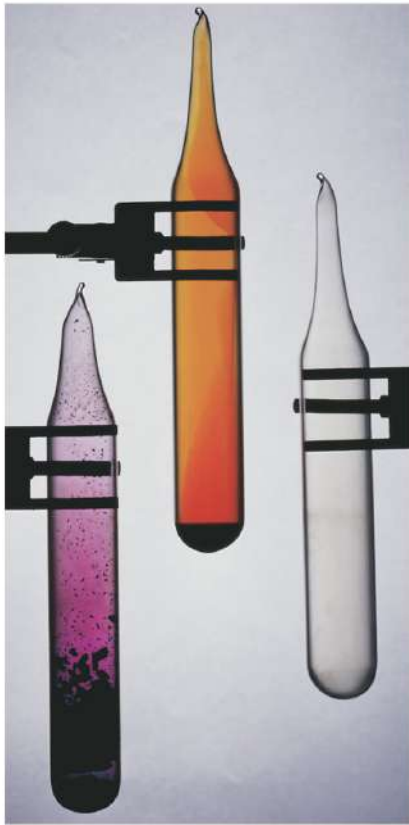
- Weaker oxidizing agent than oxygen.
- Most stable allotrope is S₈, a ringed molecule.

Group VIIA: Halogens

Element	Electron Configuration	Melting Point (°C)	Density	Atomic Radius (Å)	I_1 (kJ/mol)
Fluorine	[He]2s ² 2p ⁵	-220	1.69 g/L	0.71	1681
Chlorine	[Ne]3s ² 3p ⁵	-102	3.21 g/L	0.99	1251
Bromine	[Ar]3d ¹⁰ 4s ² 4p ⁵	-7.3	3.12 g/cm ³	1.14	1140
Iodine	[Kr]4d ¹⁰ 5s ² 5p ⁵	114	4.94 g/cm ³	1.33	1008

- Prototypical nonmetals
- Name comes from the Greek *halos* and *gennao*: “salt formers”

Group VIIA: Halogens



- Large, negative electron affinities
 - Therefore, tend to oxidize other elements easily
- React directly with metals to form metal halides
- Chlorine added to water supplies to serve as disinfectant

Group VIIIA: Noble Gases

Element	Electron Configuration	Boiling Point (K)	Density (g/L)	Atomic Radius* (Å)	I_1 (kJ/mol)
Helium	$1s^2$	4.2	0.18	0.32	2372
Neon	$[\text{He}]2s^22p^6$	27.1	0.90	0.69	2081
Argon	$[\text{Ne}]3s^23p^6$	87.3	1.78	0.97	1521
Krypton	$[\text{Ar}]3d^{10}4s^24p^6$	120	3.75	1.10	1351
Xenon	$[\text{Kr}]4d^{10}5s^25p^6$	165	5.90	1.30	1170
Radon	$[\text{Xe}]4f^{14}5d^{10}6s^26p^6$	211	9.73	1.45	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.

- Astronomical ionization energies
- Positive electron affinities
 - Therefore, relatively unreactive
- Monatomic gases

Group VIIIA: Noble Gases

- Xe forms three compounds:
 - XeF_2
 - XeF_4 (at right)
 - XeF_6
- Kr forms only one stable compound:
 - KrF_2
- The unstable HArF was synthesized in 2000.

