Physics 123 – April 22, 2013

Time Independent Schödinger equation (1d, nonrelativistic)

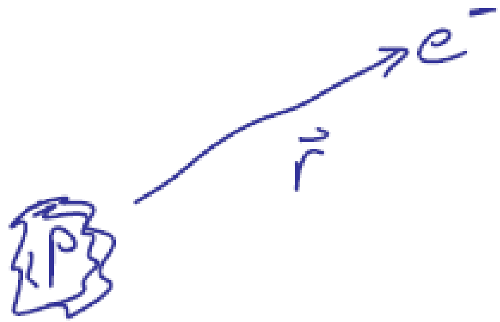
$$-\frac{\hbar^2}{2m}\frac{\partial^2 \psi(x)}{\partial x^2} + V(x)\,\psi(x) = E\,\psi(x)$$

$|\psi(x)|^2 dv \equiv$ probability of finding particle in dv

$$\int_{\text{all space}} |\psi(x)|^2 dv = 1$$ Particle is <u>Someplace</u>

Sub in for V, Solve for ψ and E

H atom



$$V(r) = \frac{1}{4\pi\epsilon_0}\frac{|e|^2}{r^2}$$

Schr. eqn in 3d

$$-\frac{\hbar^2}{2m}\nabla^2\psi + V\psi = E\psi$$

plug in V and solve

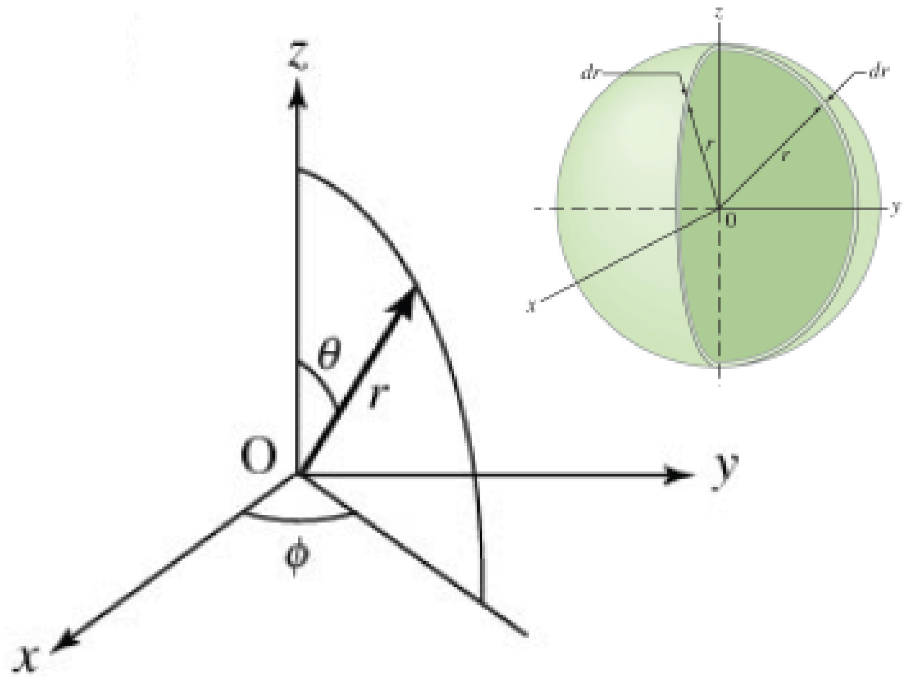
need to use spherical polar coordinates

Spherical Coordinates

$$x = r\sin\theta\cos\varphi$$

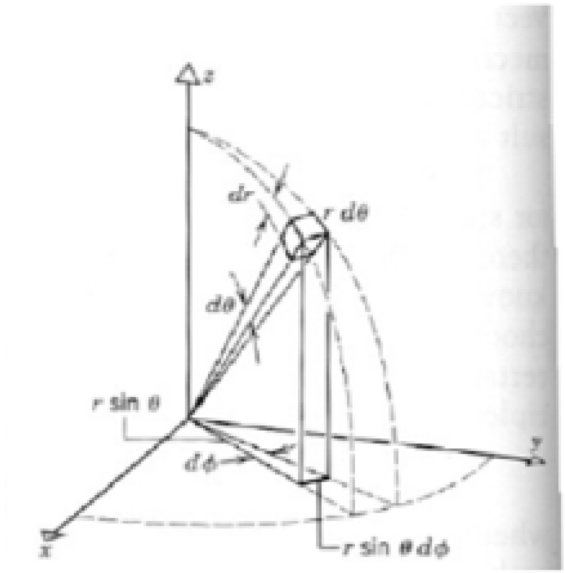
$$y = r\sin\theta\sin\varphi$$

$$z = r\cos\theta$$



$$\frac{\partial^2 f}{\partial x^2} + \frac{\partial^2 f}{\partial y^2} + \frac{\partial^2 f}{\partial z^2} =$$

$$= \frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2\frac{\partial f}{\partial r}\right) + \frac{1}{r^2\sin\theta}\frac{\partial}{\partial\theta}\left(\sin\theta\frac{\partial f}{\partial\theta}\right) + \frac{1}{r^2\sin^2\theta}\frac{\partial^2 f}{\partial\varphi^2}$$



$$\psi \longrightarrow \psi(r, \theta, \phi)$$

$$V(r) = -\frac{1}{4\pi\epsilon_0}\frac{|e|^2}{r^2}$$

$$-\frac{\hbar^2}{2m}\left[\frac{1}{r^2}\frac{\partial}{\partial r} r^2 \frac{\partial \psi}{\partial r} + \frac{1}{r^2 \sin^2\theta}\frac{\partial^2 \psi}{\partial \phi^2} + \frac{1}{r^2 \sin\theta}\frac{\partial}{\partial \theta}\sin\theta\frac{\partial \psi}{\partial \theta}\right] - \frac{1}{4\pi\epsilon_0}\frac{|e|^2}{r^2}\psi = E\psi$$

Now solve

Can be solved exactly . . .

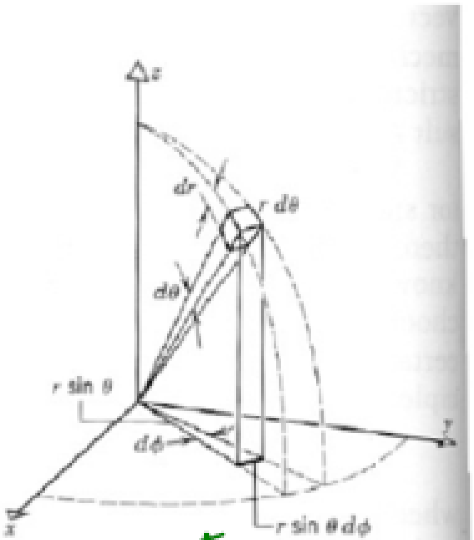
$\psi(r,\theta,\varphi) \longrightarrow \psi(R)\,\psi(\Theta)\,\psi(\Phi)$

Can separate Schr. equation into eqns for $\psi(R)$, $\psi(\Theta)$, $\psi(\Phi)$ + Solve

"Energy" or "principle" quantum # $n = 1, 2, 3 \cdots$

"orbital" quantum # $l = 0, 1, \cdots n-1$

"Magnetic" quantum # $-l, -(l-1), \cdots 0, 1, \cdots, l-1, l$



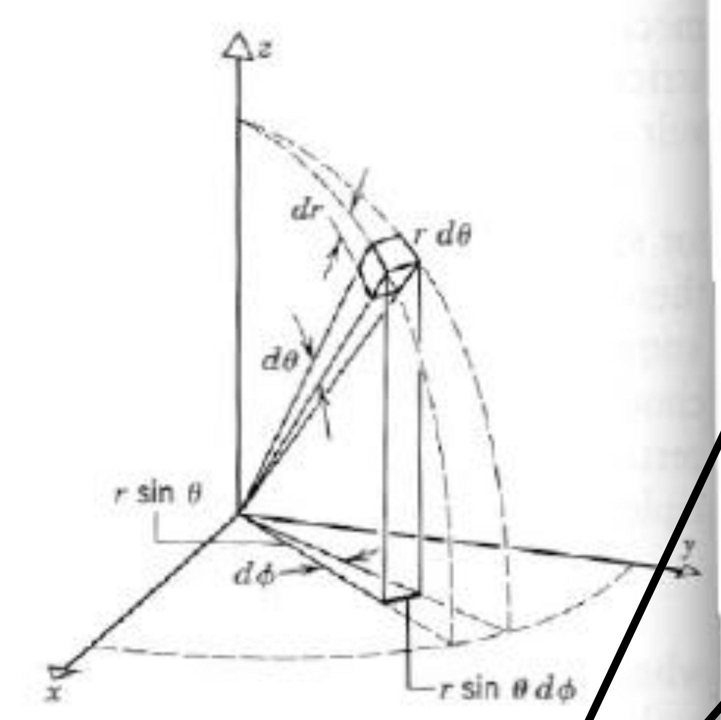
Bound system
↳ Discrete states

R, Φ, Θ parts tied together

$n \rightsquigarrow$ Similar to Bohr's n

Table 7.1 Some Hydrogen Atom Wave Functions

n	l	m_l	$R(r)$	$\Theta(\theta)$	$\Phi(\phi)$
1	0	0	$\frac{2}{a_0^{3/2}} e^{-r/a_0}$	$\frac{1}{\sqrt{2}}$	$\frac{1}{\sqrt{2\pi}}$
2	0	0	$\frac{1}{(2a_0)^{3/2}}\left(2 - \frac{r}{a_0}\right) e^{-r/2a_0}$	$\frac{1}{\sqrt{2}}$	$\frac{1}{\sqrt{2\pi}}$
2	1	0	$\frac{1}{\sqrt{3}(2a_0)^{3/2}} \frac{r}{a_0} e^{-r/2a_0}$	$\sqrt{\frac{3}{2}} \cos\theta$	$\frac{1}{\sqrt{2\pi}}$
2	1	±1	$\frac{1}{\sqrt{3}(2a_0)^{3/2}} \frac{r}{a_0} e^{-r/2a_0}$	$\frac{\sqrt{3}}{2} \sin\theta$	$\frac{1}{\sqrt{2\pi}} e^{\pm i\phi}$



Energy or principal quantum number

n = 1, 2, 3 …

Orbital quantum number

l = 0, 1, … n-1

Magnetic quantum number

-l, -|l-1|, …, 0, 1, … l-1, l

Table 7.1 Some Hydrogen Atom Wave Functions

n	l	m_l	$R(r)$	$\Theta(\theta)$	$\Phi(\phi)$
1	0	0	$\frac{2}{a_0^{3/2}} e^{-r/a_0}$	$\frac{1}{\sqrt{2}}$	$\frac{1}{\sqrt{2\pi}}$
2	0	0	$\frac{1}{(2a_0)^{3/2}}\left(2-\frac{r}{a_0}\right) e^{-r/2a_0}$	$\frac{1}{\sqrt{2}}$	$\frac{1}{\sqrt{2\pi}}$
2	1	0	$\frac{1}{\sqrt{3}(2a_0)^{3/2}} \frac{r}{a_0} e^{-r/2a_0}$	$\sqrt{\frac{3}{2}}\cos\theta$	$\frac{1}{\sqrt{2\pi}}$
2	1	± 1	$\frac{1}{\sqrt{3}(2a_0)^{3/2}} \frac{r}{a_0} e^{-r/2a_0}$	$\frac{\sqrt{3}}{2}\sin\theta$	$\frac{1}{\sqrt{2\pi}} e^{\pm i\phi}$

$$\Psi_{n,l,m_l}(\mathbf{r}) = R_{n,l}(r)Y_{l,m_l}(\theta,\phi)$$

$n=1 \quad l=0 \quad m_l=0 \qquad \psi_{100} = \frac{2}{\sqrt{r_0^3}} e^{-r/r_0} \sqrt{\frac{1}{4\pi}}$

$n=2 \quad l=0 \quad m_l=0 \qquad \psi_{200} = \frac{1}{\sqrt{2r_0^3}} \left(1 - \frac{r}{2r_0}\right) e^{-r/2r_0} \sqrt{\frac{1}{4\pi}}$

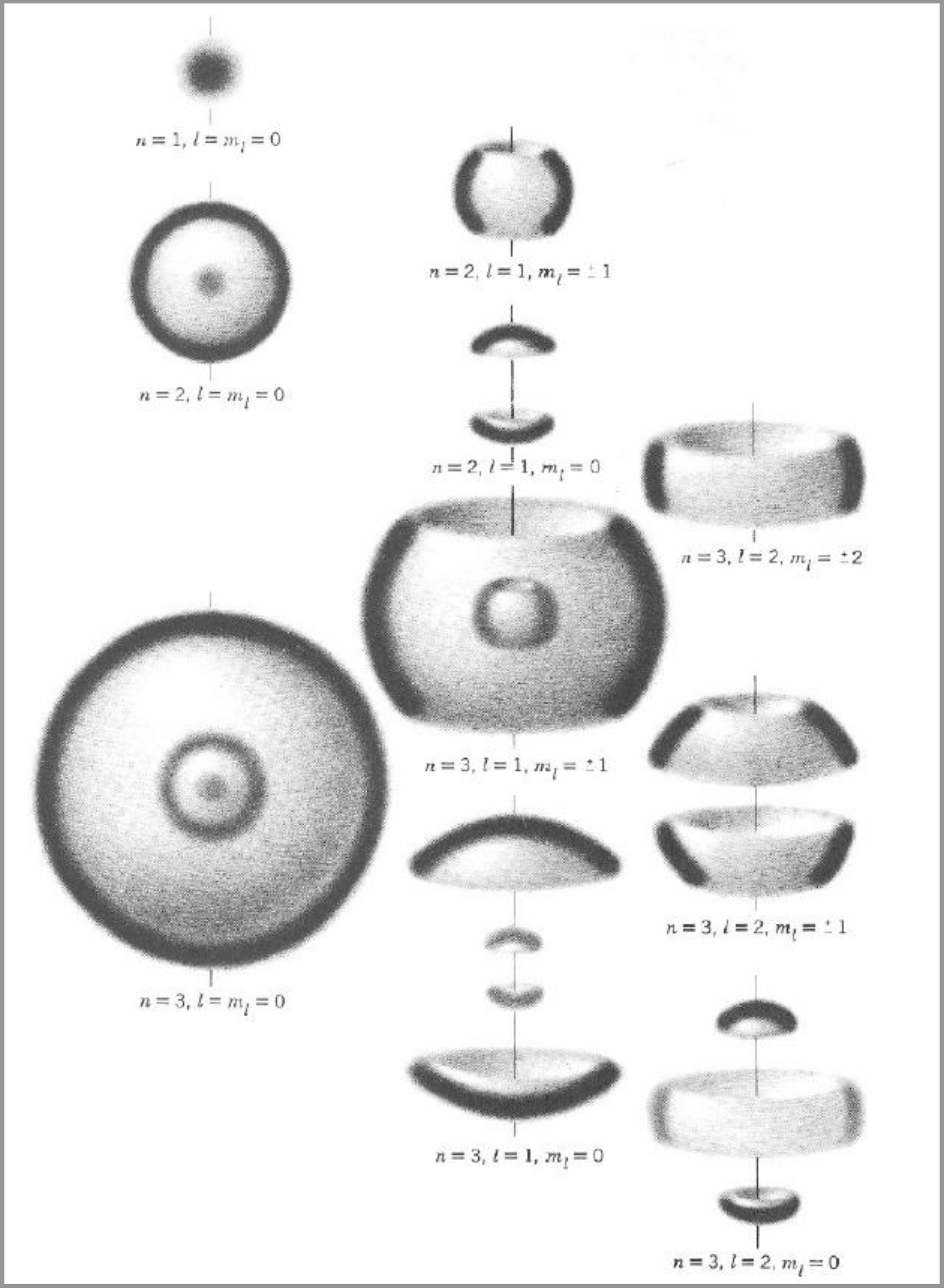
$n=2 \quad l=1 \quad m_l=+1 \qquad \psi_{211} = \frac{1}{2\sqrt{6r_0^3}} \left(\frac{r}{r_0}\right) e^{-r/2r_0} \sqrt{\frac{3}{8\pi}} \sin\theta \, e^{i\varphi}$

$n=2 \quad l=1 \quad m_l=0 \qquad \psi_{210} = \frac{1}{2\sqrt{6r_0^3}} \left(\frac{r}{r_0}\right) e^{-r/2r_0} \sqrt{\frac{3}{4\pi}} \cos\theta$

$n=2 \quad l=1 \quad m_l=-1 \qquad \psi_{21-1} = \frac{1}{2\sqrt{6r_0^3}} \left(\frac{r}{r_0}\right) e^{-r/2r_0} \sqrt{\frac{3}{8\pi}} \sin\theta \, e^{-i\varphi}$

Probability distributions for several allowed atomic states for the 1-electron atom

Increasing n adds new radial layers, l=0 give spherical symmetry, l not 0 brings in angular dependence



Only discrete energies and spatial STATES allowed for the electron to occupy → orbital

Higher energy

low energy

"degenerate" + slightly higher energy

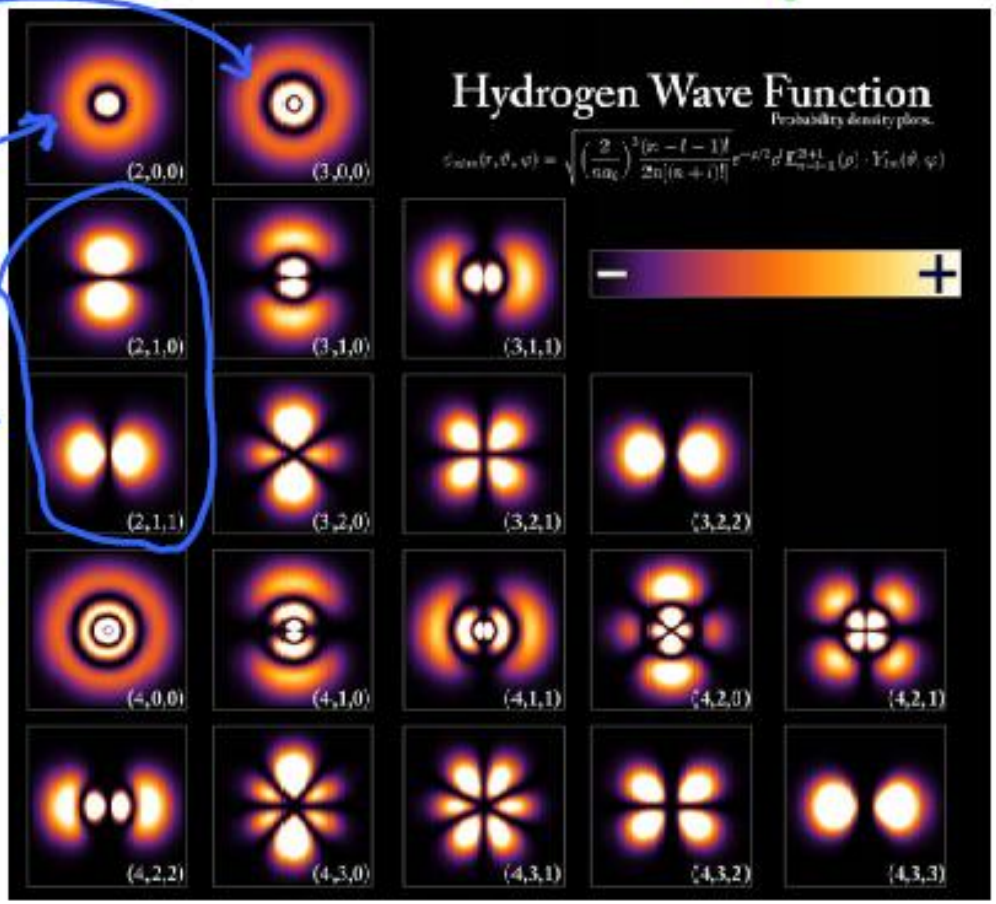
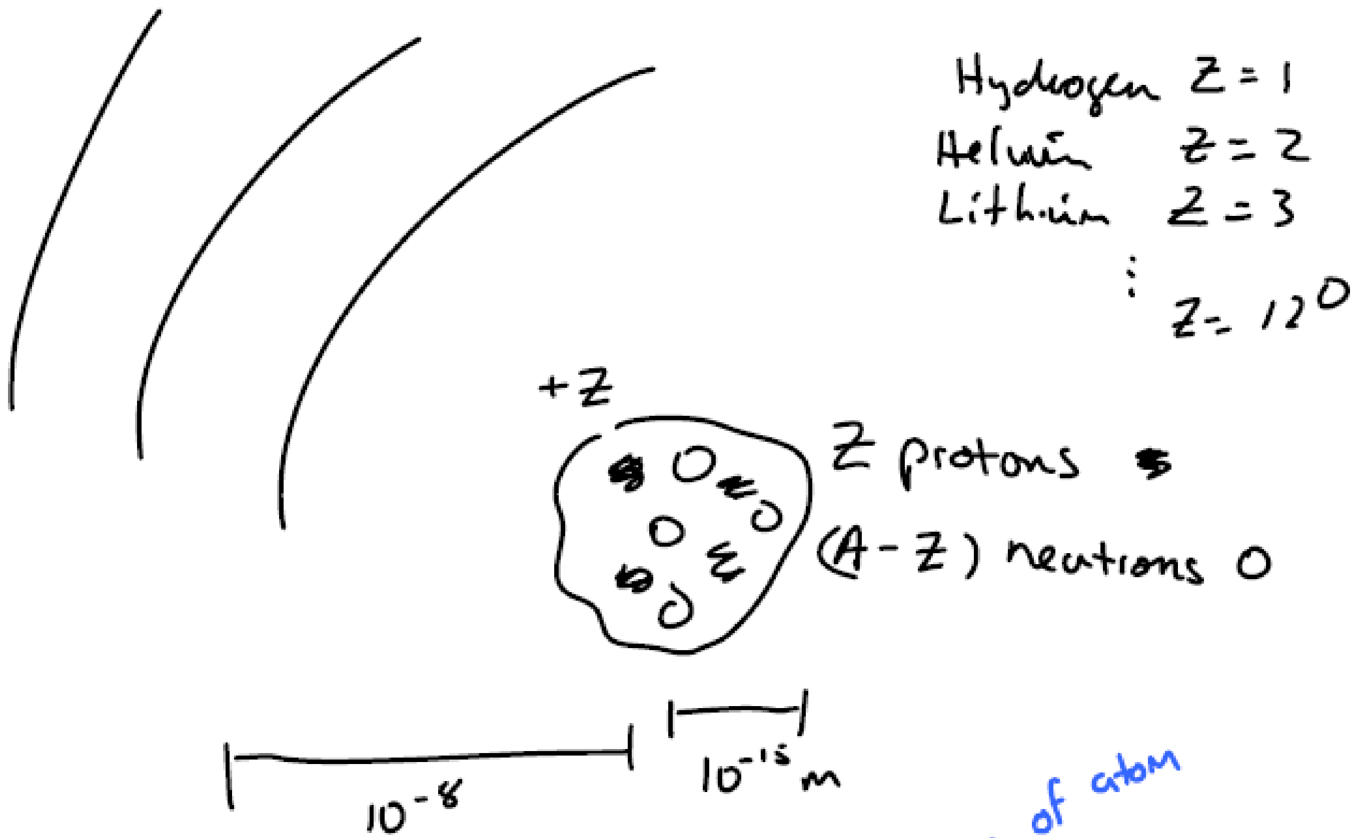
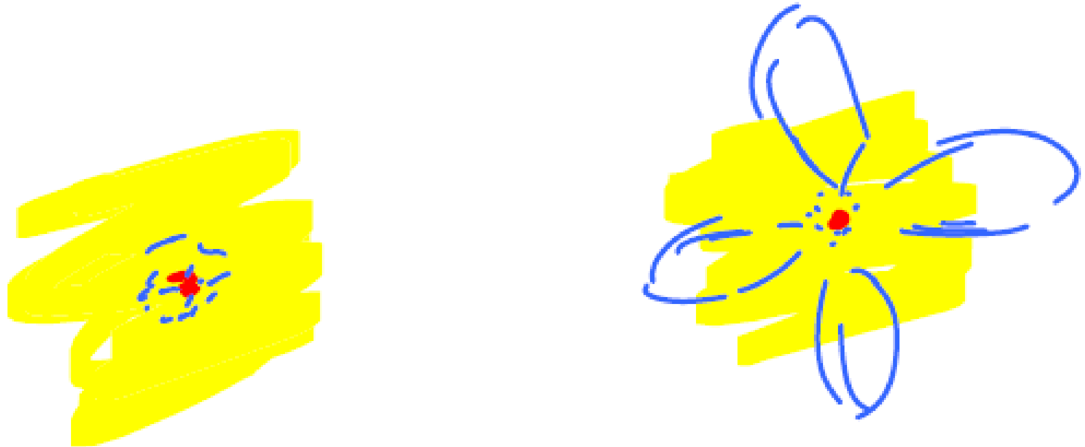


figure from http://en.wikipedia.org/wiki/File:Hydrogen_Density_Plots.png



Basic Structure of atom



as Z increases → # electrons increase

↑ # protons in nucleus

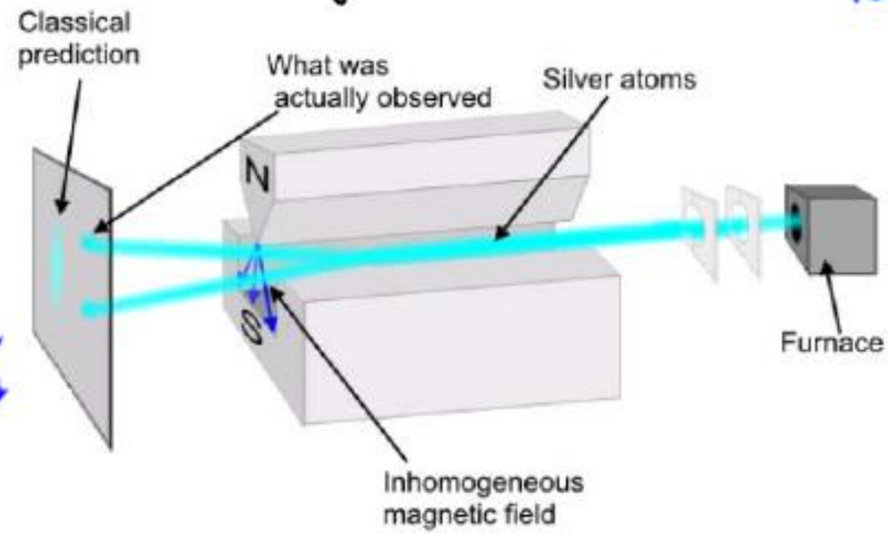
How do these electrons populate the available orbitals?

To Answer this we need to investigate

Particle Promiscuity

Stern-Gerlach experiment — 1922

→ Discovery that electrons have spin



Spin

Diagram from Wikipedia

Otto Stern

-wikipedia

"If this nonsense from Bohr will prove to be right we will quit physics."
(Stern vowed in 1913)

as quoted in Phys. Today Dec 03

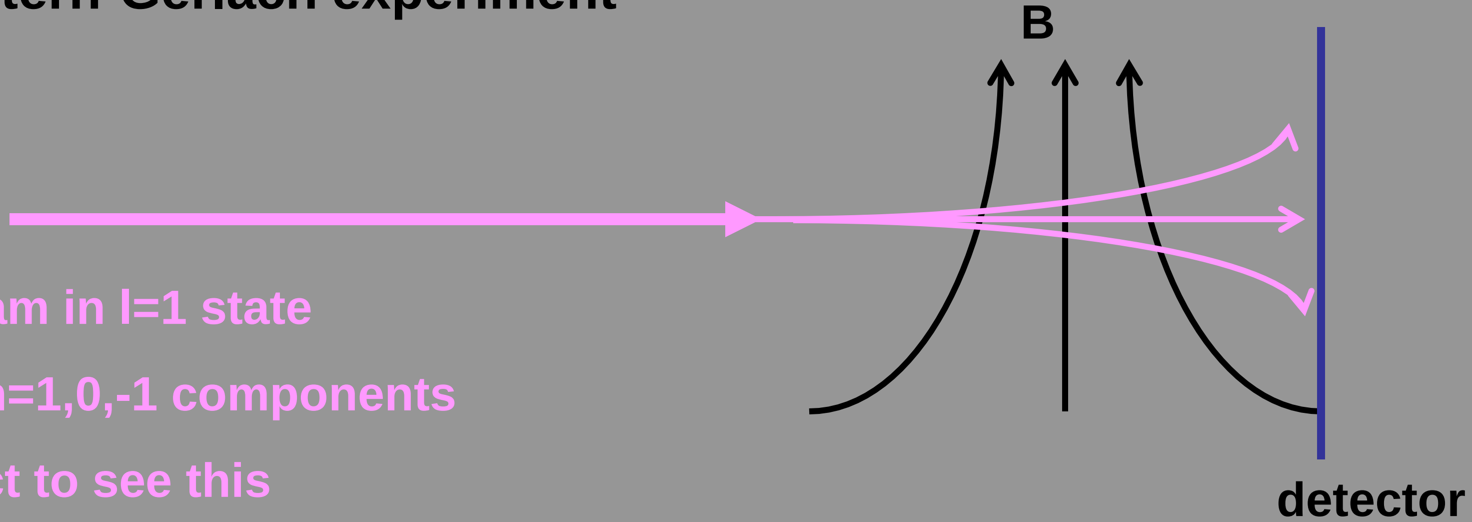
Walther Gerlach

from phys Today article (Dec. 03)

General Quant. Mech. result regarding force on magnetic dipole in a non-uniform magnetic field

$$\vec{F}_z = \frac{\partial B_z}{\partial z} | \vec{\mu}_z | = \frac{\partial B_z}{\partial z} m$$

Stern-Gerlach experiment



e- beam in l=1 state

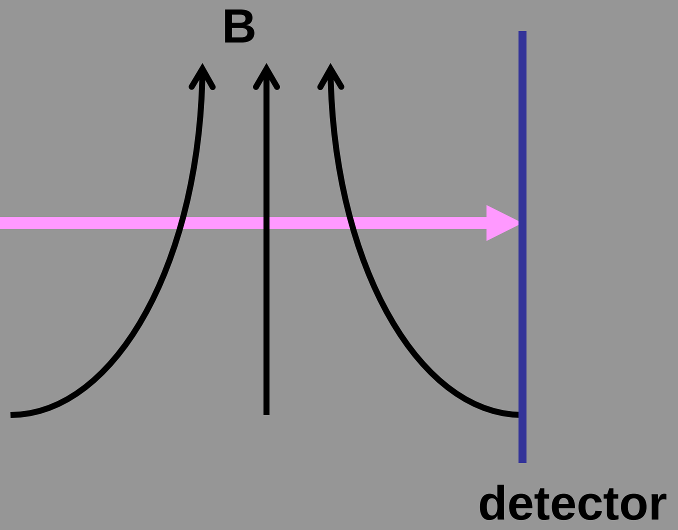
has m=1,0,-1 components

expect to see this

General Quant. Mech. result regarding force on magnetic dipole in a non-uniform magnetic field

$$\vec{F}_z = \frac{\partial B_z}{\partial z} |\vec{\mu}_z| = \frac{\partial B_z}{\partial z} m$$

Stern-Gerlach experiment



e- beam in l=0 state

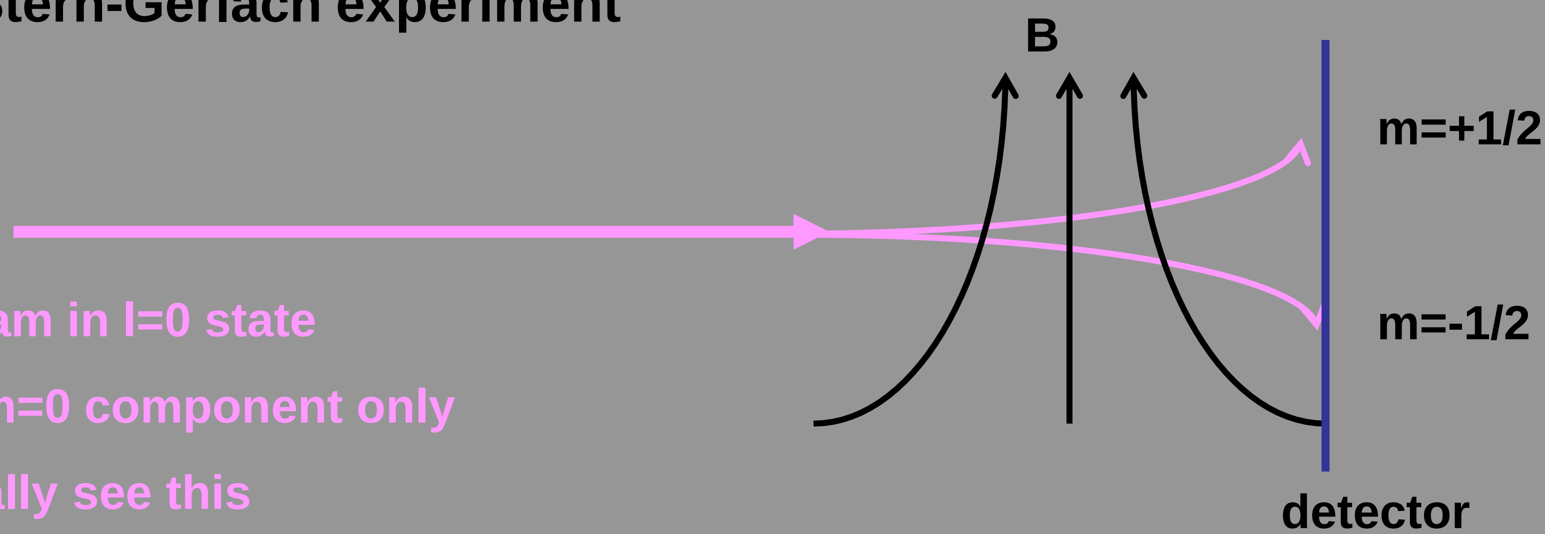
Has m=0 component only

expect to see this

SURPRISE! … fundamental particle have an intrinsic magnetic moment. Call it spin.

$$\vec{F}_z = \frac{\partial B_z}{\partial z} |\vec{\mu}_z| = \frac{\partial B_z}{\partial z} m$$

Stern-Gerlach experiment

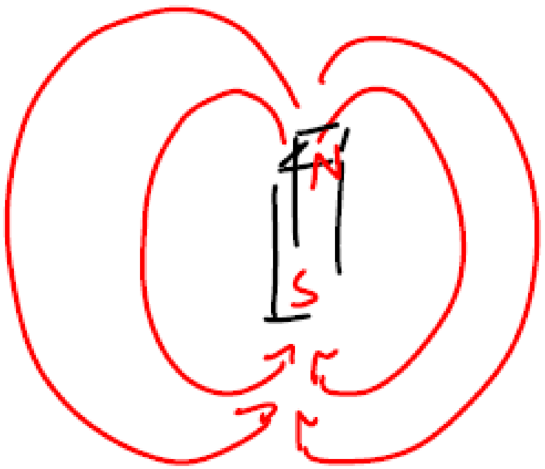


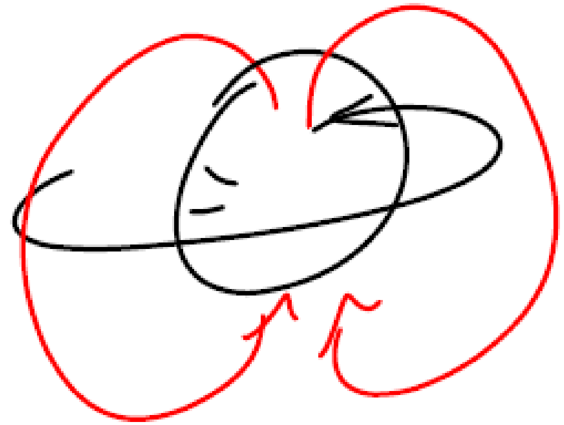
e- beam in l=0 state

Has m=0 component only

Actually see this

Particles have intrinsic **Spin**





Spin is quantized

$0, \frac{1}{2}, 1, \frac{3}{2}, 2, \frac{5}{2}$

Intrinsic spin - two varieties

Huge effect on multi-electron atoms

Fermions = half integral spin, such as 1/2, 3/2, 5/2, … , 73/2 …

protons, neutrons, electrons are all fermions (s=1/2)

no two fermions can occupy the same exact quantum state

Bosons = integral spin, such as 0, 1, 2 …

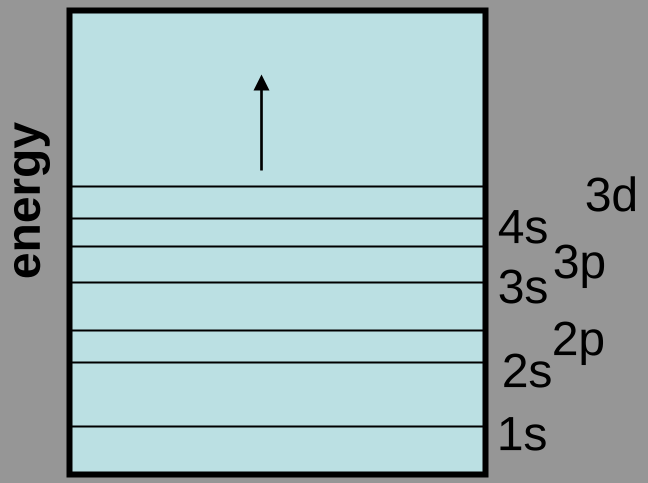
photons (s=1) and pions (s=0) are examples of bosons

bosons can occupy the same exact quantum state

Rules for Filling of state for multi-electron atom
n, l, m_l, m_s

Spectroscopic notation - s: l=0, p: l=1, d: l=2, f: l=3, …

- **No two electrons in same state (Pauli exclusion)**
- **Electrons go into the state with the lowest possible energy (Aufbau)**
- **Within a sublevel, electrons will have their spin unpaired as much as possible (due to spin-spin interaction contribution to energy)**



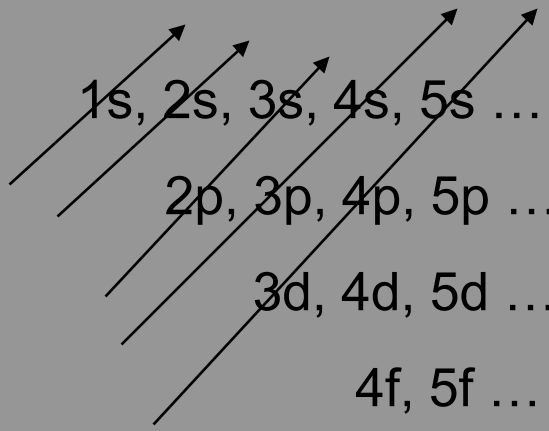
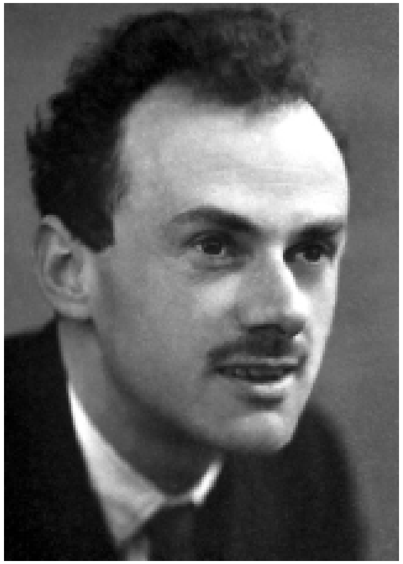


TABLE 39–1 Quantum Numbers for an Electron

Name	Symbol	Possible Values
Principal	n	$1, 2, 3, \cdots, \infty$.
Orbital	ℓ	For a given n: ℓ can be $0, 1, 2, \cdots, n-1$.
Magnetic	m_ℓ	For given n and ℓ: m_ℓ can be $\ell, \ell-1, \cdots, 0, \cdots, -\ell$.
Spin	m_s	For each set of n, ℓ, and m_ℓ: m_s can be $+\frac{1}{2}$ or $-\frac{1}{2}$.

		K shell	L shell				M shell				
Energy level (n)		1	2				3				. . .
Sublevel (ℓ)		s	s	p			s	p			. . .
Z = #e⁻				$m_\ell=-1$	$m_\ell=0$	$m_\ell=1$					
1	H	↑	—	—	—	—	—	—	—	—	$1s^1$
2	He	↑↓	—	—	—	—	—	—	—	—	$1s^2$
3	Li	↑↓	↑	—	—	—	—	—	—	—	$1s^2 2s^1$
4	Be	↑↓	↑↓	—	—	—	—	—	—	—	$1s^2 2s^2$
5	B	↑↓	↑↓	↑	—	—	—	—	—	—	$1s^2 2s^2 2p^1$
6	C	↑↓	↑↓	↑	↑	—	—	—	—	—	
7	N	↑↓	↑↓	↑	↑	↑	—	—	—	—	
8	O	↑↓	↑↓	↑↓	↑	↑	—	—	—	—	$1s^2 2s^2 2p^4$
9	F	↑↓	↑↓	↑↓	↑↓	↑	—	—	—	—	
10	Ne	↑↓	↑↓	↑↓	↑↓	↑↓	—	—	—	—	
11	Na	↑↓	↑↓	↑↓	↑↓	↑↓	↑	—	—	—	$1s^2 2s^2 2p^6 3s^1$
	⋮				⋮						⋮

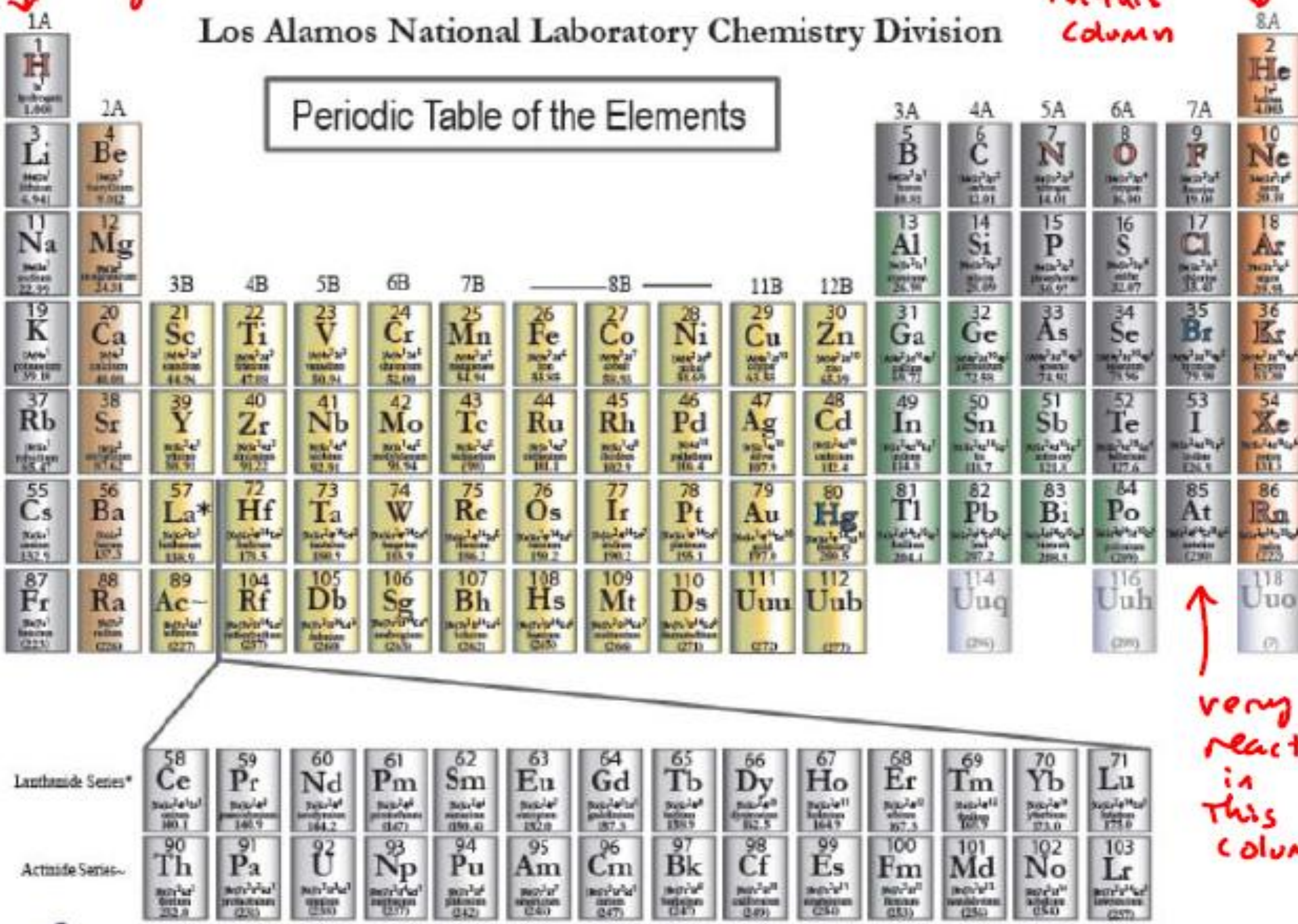


P.A.M. Dirac – on the development of quantum mechanics

"The underlying laws necessary for the mathematical theory of a large part of physics and the whole of chemistry are thus completely known."

very reactive in this column

very inert in this column



very reactive in this column

Los Alamos NATIONAL LABORATORY

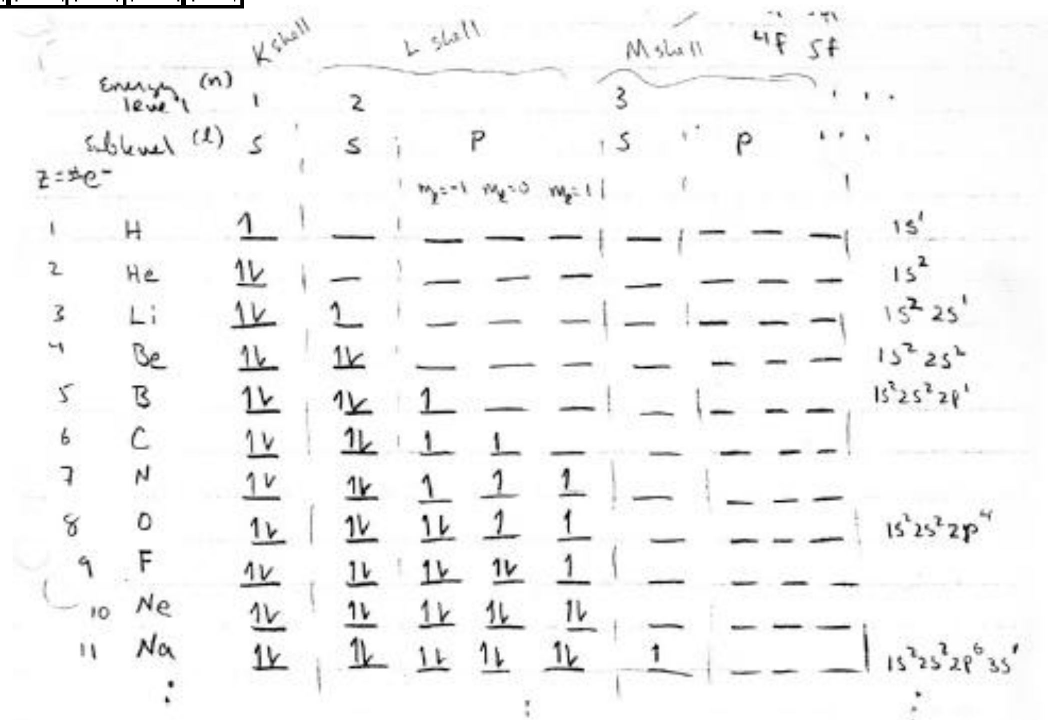
CHEMISTRY

element names in blue are liquids at room temperature
element names in red are gases at room temperature
element names in black are solids at room temperature

I A																	O
1 H 1.0079	II A											III A	IV A	V A	VI A	VII A	2 He 4.00260
3 Li 6.94	4 Be 9.01218											5 B 10.811	6 C 12.011	7 N 14.0067	8 O 15.9994	9 F 18.998403	10 Ne 20.179
11 Na 22.98977	12 Mg 24.305	III B	IV B	V B	VI B	VII B	VIII			I B	II B	13 Al 26.98154	14 Si 28.0855	15 P 30.97376	16 S 32.066	17 Cl 35.453	18 Ar 39.948
19 K 39.0983	20 Ca 40.08	21 Sc 44.9559	22 Ti 47.88	23 V 50.9415	24 Cr 51.996	25 Mn 55.9381	26 Fe 55.847	27 Co 58.9332	28 Ni 58.69	29 Cu 63.546	30 Zn 65.39	31 Ga 69.723	32 Ge 72.61	33 As 74.9216	34 Se 78.96	35 Br 79.904	36 Kr 83.80
37 Rb 85.4678	38 Sr 87.62	39 Y 88.9059	40 Zr 91.224	41 Nb 92.9064	42 Mo 95.94	43 Tc 98.9072	44 Ru 101.07	45 Rh 102.9055	46 Pd 106.42	47 Ag 107.868	48 Cd 112.41	49 In 114.82	50 Sn 118.710	51 Sb 121.75	52 Te 127.60	53 I 126.9047	54 Xe 131.30
55 Cs 132.9054	56 Ba 137.33	57 La 138.33	72 Hf 178.49	73 Ta 180.9479	74 W 183.85	75 Re 186.207	76 Os 190.2	77 Ir 192.22	78 Pt 195.08	79 Au 196.9665	80 Hg 200.59	81 Tl 204.383	82 Pb 207.2	83 Bi 208.9804	84 Po (209)	85 At (210)	86 Rn (222)
87 Fr (223)	88 Ra (226.0254)	89 Ac (227)															

58 Ce 140.12	59 Pr 140.9077	60 Nd 144.24	61 Pm (145)	62 Sm 150.4	63 Eu 151.965	64 Gd 157.25	65 Tb 158.9254	66 Dy 162.50	67 Ho 164.9303	68 Er 167.26	69 Tm 168.9342	70 Yb 173.04	71 Lu 174.967
90 Th 232.0381	91 Pa (231.036)	92 U 238.029	93 Np 237.0482	94 Pu (244.069)	95 Am (243.06)	96 Cm (247.070)	97 Bk (247.070)	98 Cf (251.08)	99 Es (252.083)	100 Fm (257.095)	101 Md (258.18)	102 No (259.101)	103 Lr (260.11)

47 Ag 107.868 — Atomic number, Symbol, Atomic mass



Check out

http:www.chemicool.com

Interactive periodic chart

47 — Atomic number
Ag — Symbol
107.868 — Atomic mass

I A	II A	III B	IV B	V B	VI B	VII B	VIII	VIII	VIII	I B	II B	III A	IV A	V A	VI A	VII A	O
1 H 1.0079																	2 He 4.00260
3 Li 6.94	4 Be 9.01218											5 B 10.811	6 C 12.011	7 N 14.0067	8 O 15.9994	9 F 18.998403	10 Ne 20.179
11 Na 22.98977	12 Mg 24.305											13 Al 26.98154	14 Si 28.0855	15 P 30.97376	16 S 32.066	17 Cl 35.453	18 Ar 39.948
19 K 39.0983	20 Ca 40.08	21 Sc 44.9559	22 Ti 47.88	23 V 50.9415	24 Cr 51.996	25 Mn 54.9380	26 Fe 55.847	27 Co 58.9332	28 Ni 58.69	29 Cu 63.546	30 Zn 65.39	31 Ga 69.723	32 Ge 72.61	33 As 74.9216	34 Se 78.96	35 Br 79.904	36 Kr 83.80
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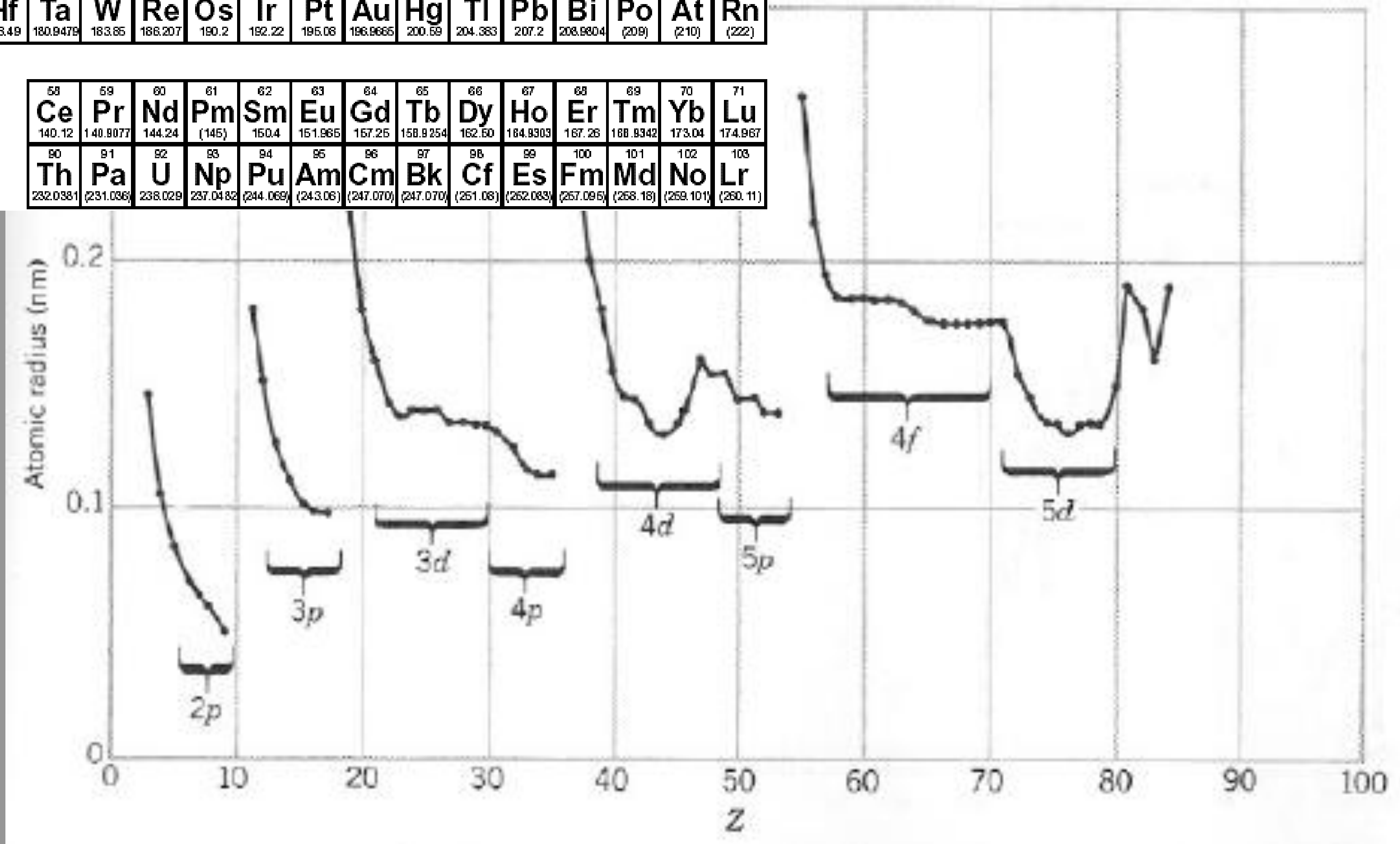

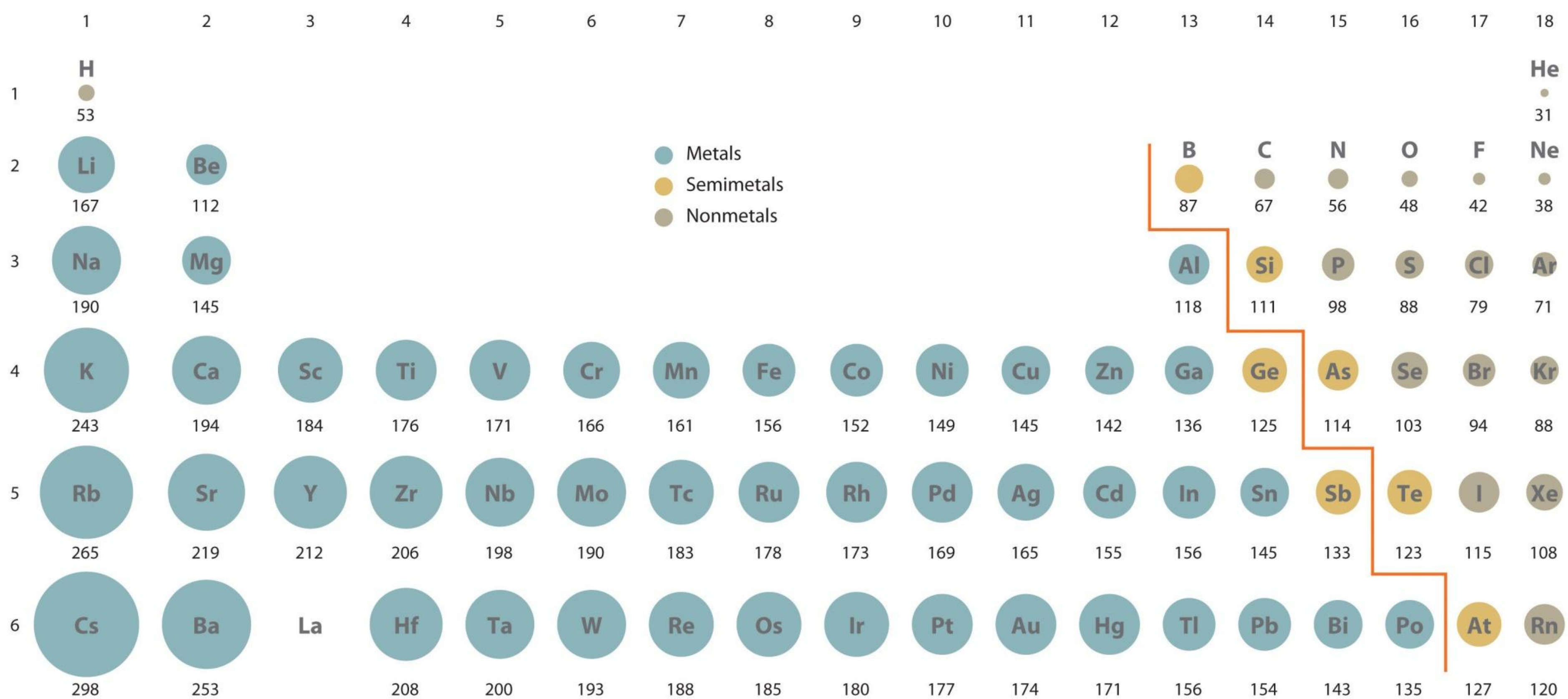
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H 53
He 31
2
Li 167
Be 112
Metals
Semimetals
Nonmetals
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C 67
N 56
O 48
F 42
Ne 38
3
Na 190
Mg 145
Al 118
Si 111
P 98
S 88
Cl 79
Ar 71
4
K 243
Ca 194
Sc 184
Ti 176
V 171
Cr 166
Mn 161
Fe 156
Co 152
Ni 149
Cu 145
Zn 142
Ga 136
Ge 125
As 114
Se 103
Br 94
Kr 88
5
Rb 265
Sr 219
Y 212
Zr 206
Nb 198
Mo 190
Tc 183
Ru 178
Rh 173
Pd 169
Ag 165
Cd 155
In 156
Sn 145
Sb 133
Te 123
I 115
Xe 108
6
Cs 298
Ba 253
La
Hf 208
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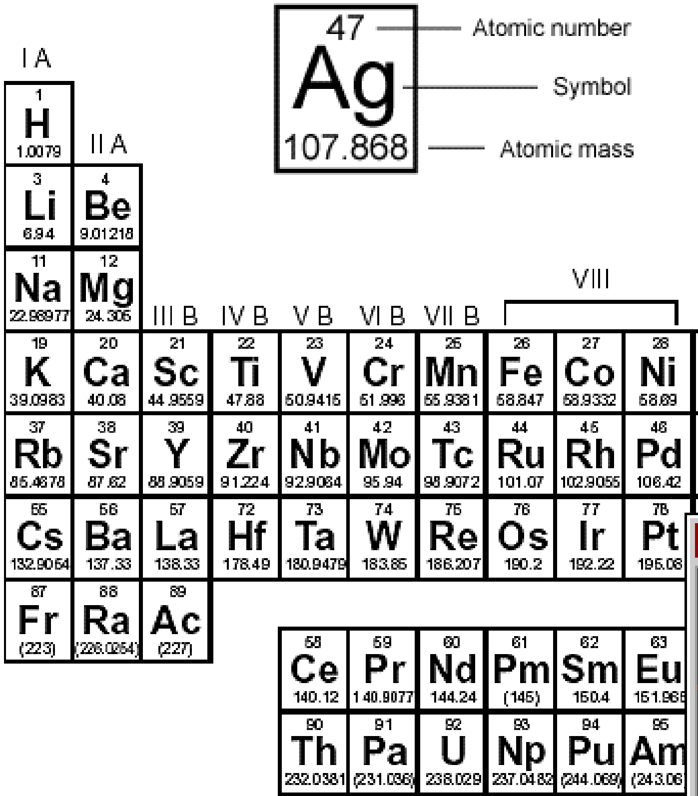
47 Ag 107.868
Atomic number
Symbol
Atomic mass
IA
IIA
IIIB IVB VB VIB VIIB
VIII
IB IIB
IIIA IVA VA VIA VIIA
O
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11 Na 22.98977
12 Mg 24.305
13 Al 26.98154
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15 P 30.97376
16 S 32.066
17 Cl 35.453
18 Ar 39.948
19 K 39.0983
20 Ca 40.08
21 Sc 44.9559
22 Ti 47.88
23 V 50.9415
24 Cr 51.996
25 Mn 55.9381
26 Fe 55.847
27 Co 58.9332
28 Ni 58.69
29 Cu 63.546
30 Zn 65.39
31 Ga 69.723
32 Ge 72.61
33 As 74.9216
34 Se 78.96
35 Br 79.904
36 Kr 83.80
37 Rb 85.4678
38 Sr 87.62
39 Y 88.9059
40 Zr 91.224
41 Nb 92.9064
42 Mo 95.94
43 Tc 98.9072
44 Ru 101.07
45 Rh 102.9055
46 Pd 106.42
47 Ag 107.868
48 Cd 112.41
49 In 114.82
50 Sn 118.710
51 Sb 121.75
52 Te 127.60
53 I 126.9047
54 Xe 131.30
55 Cs 132.9054
56 Ba 137.33
57 La 138.33
72 Hf 178.49
73 Ta 180.9479
74 W 183.85
75 Re 186.207
76 Os 190.2
77 Ir 192.22
78 Pt 195.08
87 Fr (223)
88 Ra (226.0254)
89 Ac (227)
58 Ce 140.12
59 Pr 140.9077
60 Nd 144.24
61 Pm (145)
62 Sm 150.4
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90 Th 232.0381
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92 U 238.029
93 Np 237.0482
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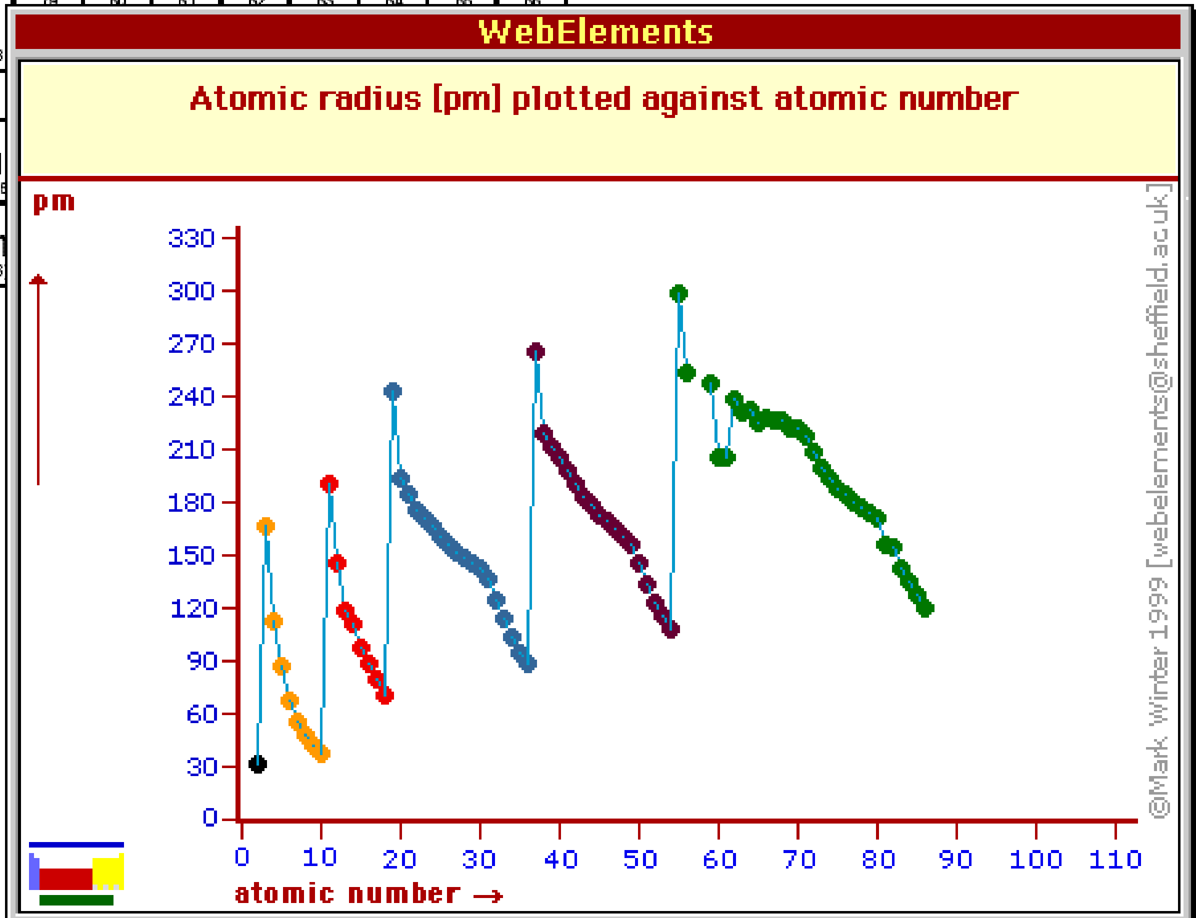
WebElements
Atomic radius [pm] plotted against atomic number
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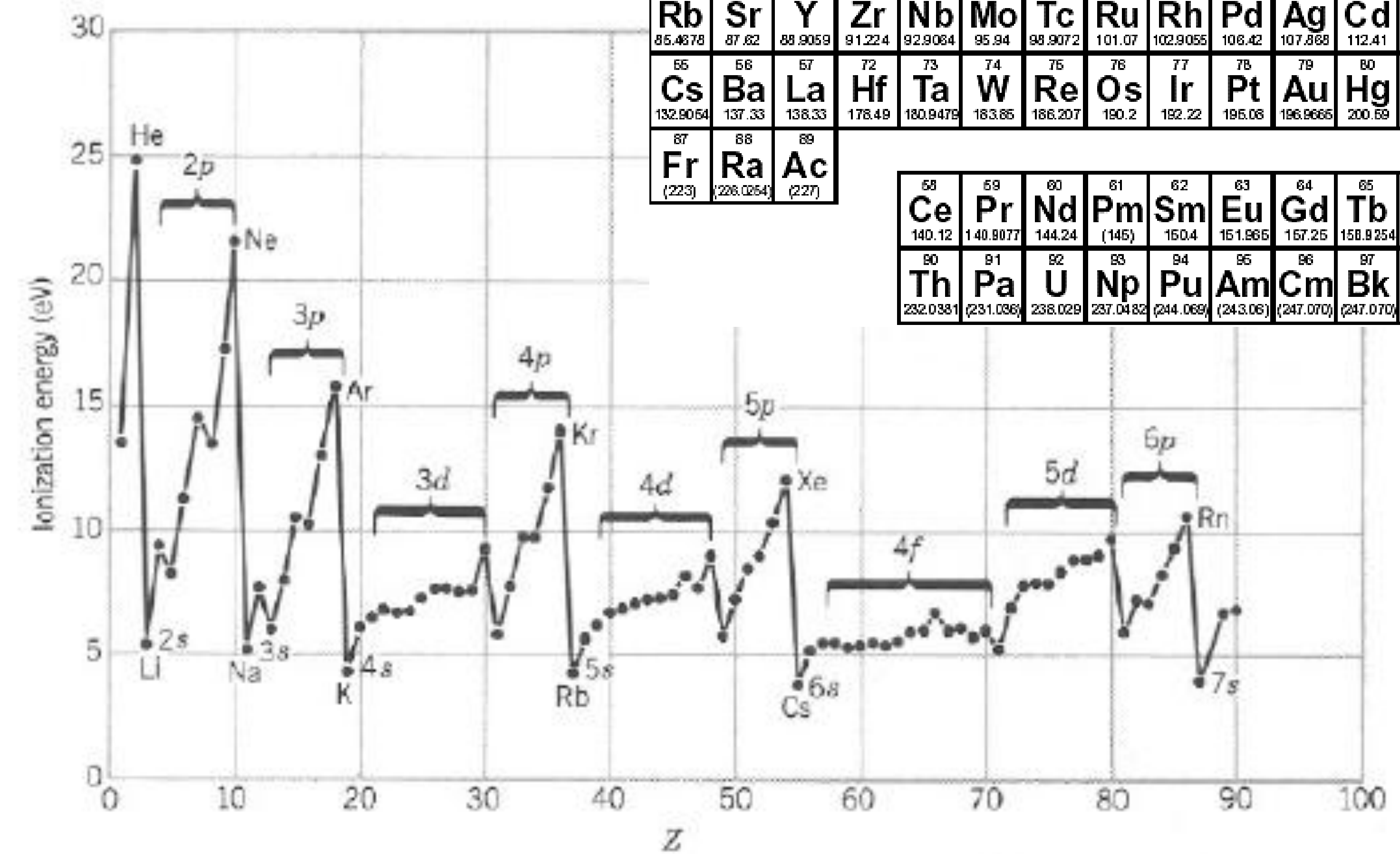
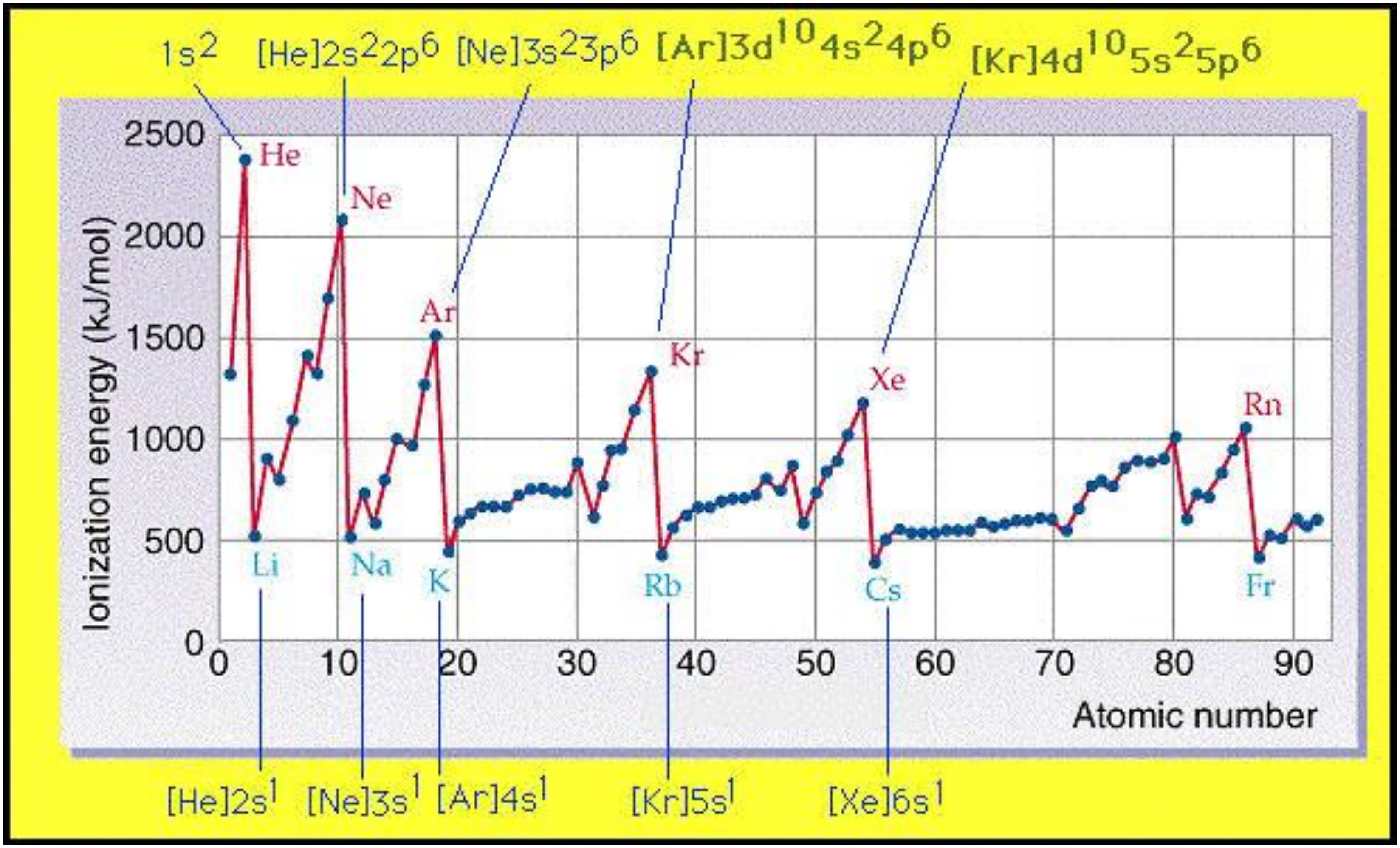
330
300
270
240
210
180
150
120
90
60
30
0
0 10 20 30 40 50 60 70 80 90 100 110
atomic number →
©Mark Winter 1999 [webelements@sheffield.ac.uk]

47 — Atomic number
Ag — Symbol
107.868 — Atomic mass

IA	IIA	IIIB	IVB	VB	VIB	VIIB	VIII	VIII	VIII	IB	IIB	IIIA	IVA	VA	VIA	VIIA	O
1 H 1.0079																	2 He 4.00260
3 Li 6.94	4 Be 9.01218											5 B 10.811	6 C 12.011	7 N 14.0067	8 O 15.9994	9 F 18.998403	10 Ne 20.179
11 Na 22.98977	12 Mg 24.305											13 Al 26.98154	14 Si 28.0855	15 P 30.97376	16 S 32.066	17 Cl 35.453	18 Ar 39.948
19 K 39.0983	20 Ca 40.08	21 Sc 44.9559	22 Ti 47.88	23 V 50.9415	24 Cr 51.996	25 Mn 54.9381	26 Fe 55.847	27 Co 58.9332	28 Ni 58.69	29 Cu 63.546	30 Zn 65.39	31 Ga 69.723	32 Ge 72.61	33 As 74.9216	34 Se 78.96	35 Br 79.904	36 Kr 83.80
37 Rb 85.4678	38 Sr 87.62	39 Y 88.9059	40 Zr 91.224	41 Nb 92.9064	42 Mo 95.94	43 Tc 98.9072	44 Ru 101.07	45 Rh 102.9055	46 Pd 106.42	47 Ag 107.868	48 Cd 112.41	49 In 114.82	50 Sn 118.710	51 Sb 121.75	52 Te 127.60	53 I 126.9047	54 Xe 131.30
55 Cs 132.9054	56 Ba 137.33	57 La 138.33	72 Hf 178.49	73 Ta 180.9479	74 W 183.85	75 Re 186.207	76 Os 190.2	77 Ir 192.22	78 Pt 195.08	79 Au 196.9665	80 Hg 200.59	81 Tl 204.383	82 Pb 207.2	83 Bi 208.9804	84 Po (209)	85 At (210)	86 Rn (222)
87 Fr (223)	88 Ra (226.0254)	89 Ac (227)															

58 Ce 140.12	59 Pr 140.9077	60 Nd 144.24	61 Pm (145)	62 Sm 150.4	63 Eu 151.965	64 Gd 157.25	65 Tb 158.9254	66 Dy 162.50	67 Ho 164.9303	68 Er 167.26	69 Tm 168.9342	70 Yb 173.04	71 Lu 174.967
90 Th 232.0381	91 Pa (231.036)	92 U 238.029	93 Np 237.0482	94 Pu (244.069)	95 Am (243.06)	96 Cm (247.070)	97 Bk (247.070)	98 Cf (251.08)	99 Es (252.083)	100 Fm (257.095)	101 Md (258.10)	102 No (259.101)	103 Lr (260.11)





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Kr
Xe
Rn
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Na
K
Rb
Cs
Fr
Ionization energy (kJ/mol)
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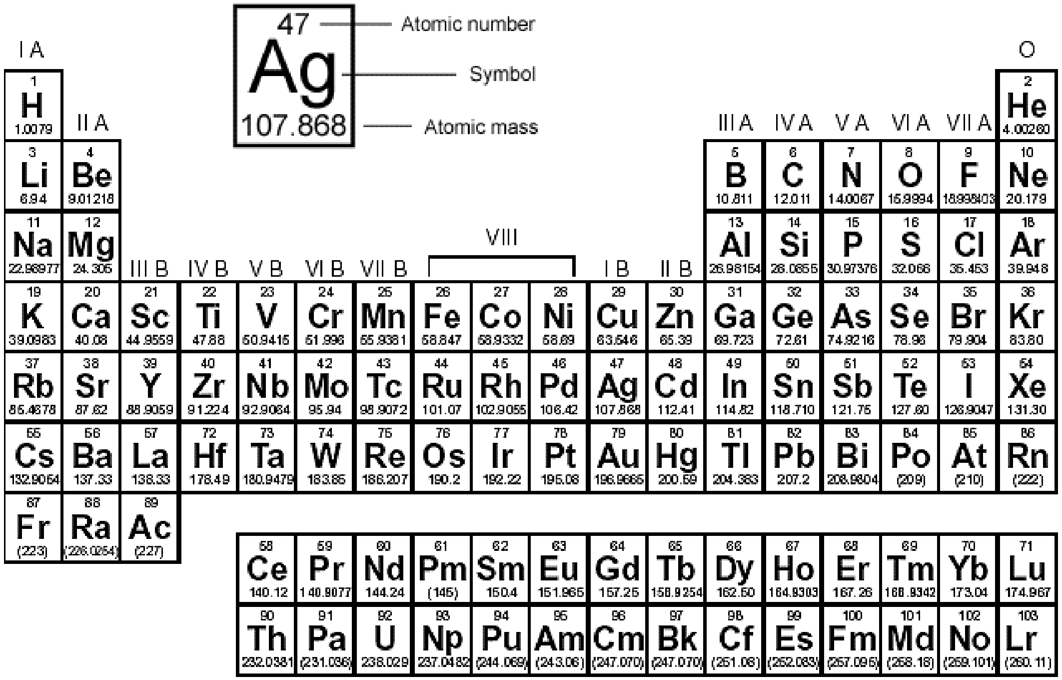
47 Ag 107.868
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III B
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V A
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VII A
O
1 H 1.0079
2 He 4.00260
3 Li 6.94
4 Be 9.01218
5 B 10.811
6 C 12.011
7 N 14.0067
8 O 15.9994
9 F 18.998403
10 Ne 20.179
11 Na 22.98977
12 Mg 24.305
13 Al 26.98154
14 Si 28.0855
15 P 30.97376
16 S 32.066
17 Cl 35.453
18 Ar 39.948
19 K 39.0983
20 Ca 40.08
21 Sc 44.9559
22 Ti 47.88
23 V 50.9415
24 Cr 51.996
25 Mn 54.9381
26 Fe 55.847
27 Co 58.9332
28 Ni 58.69
29 Cu 63.546
30 Zn 65.39
31 Ga 69.723
32 Ge 72.61
33 As 74.9216
34 Se 78.96
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36 Kr 83.80
37 Rb 85.4678
38 Sr 87.62
39 Y 88.9059
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41 Nb 92.9064
42 Mo 95.94
43 Tc 98.9072
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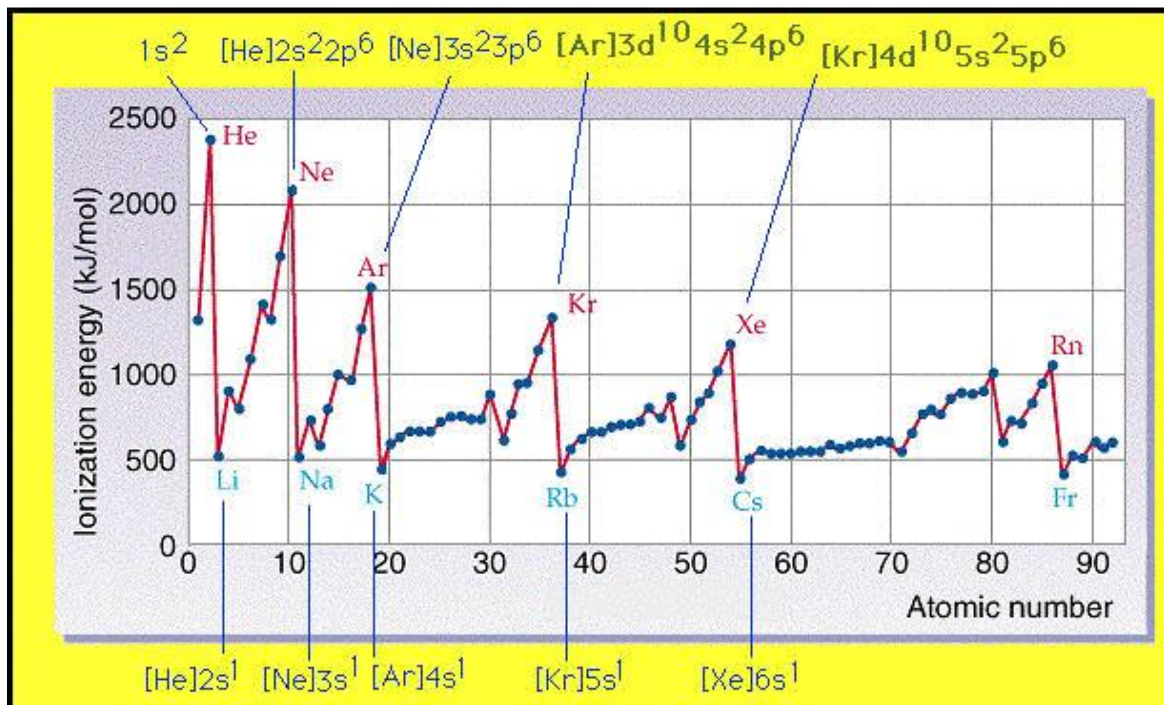
74 W 183.85
75 Re 186.207
76 Os 190.2
77 Ir 192.22
78 Pt 195.08
79 Au 196.9665
80 Hg 200.59
81 Tl 204.383
82 Pb 207.2
83 Bi 208.9804
84 Po (209)
85 At (210)
86 Rn (222)
87 Fr (223)
88 Ra 226.0254
89 Ac (227)
58 Ce 140.12
59 Pr 140.9077
60 Nd 144.24
61 Pm (145)
62 Sm 150.4
63 Eu 151.965
64 Gd 157.25
65 Tb 158.9254
66 Dy 162.50
67 Ho 164.9303
68 Er 167.26
69 Tm 168.9342
70 Yb 173.04
71 Lu 174.967
90 Th 232.0381
91 Pa (231.036)
92 U 238.029
93 Np 237.0482
94 Pu (244.069)
95 Am (243.06)
96 Cm (247.070)
97 Bk (247.070)
98 Cf (251.08)
99 Es (252.083)
100 Fm (257.095)
101 Md (258.18)
102 No (259.101)
103 Lr (260.11)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[Ne]3s23p6
[Ar]3d104s24p6
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Ne
Ar
Kr
Xe
Rn
Li
Na
K
Rb
Cs
Fr
Ionization energy (kJ/mol)
2500
2000
1500
1000
500
0
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Atomic number
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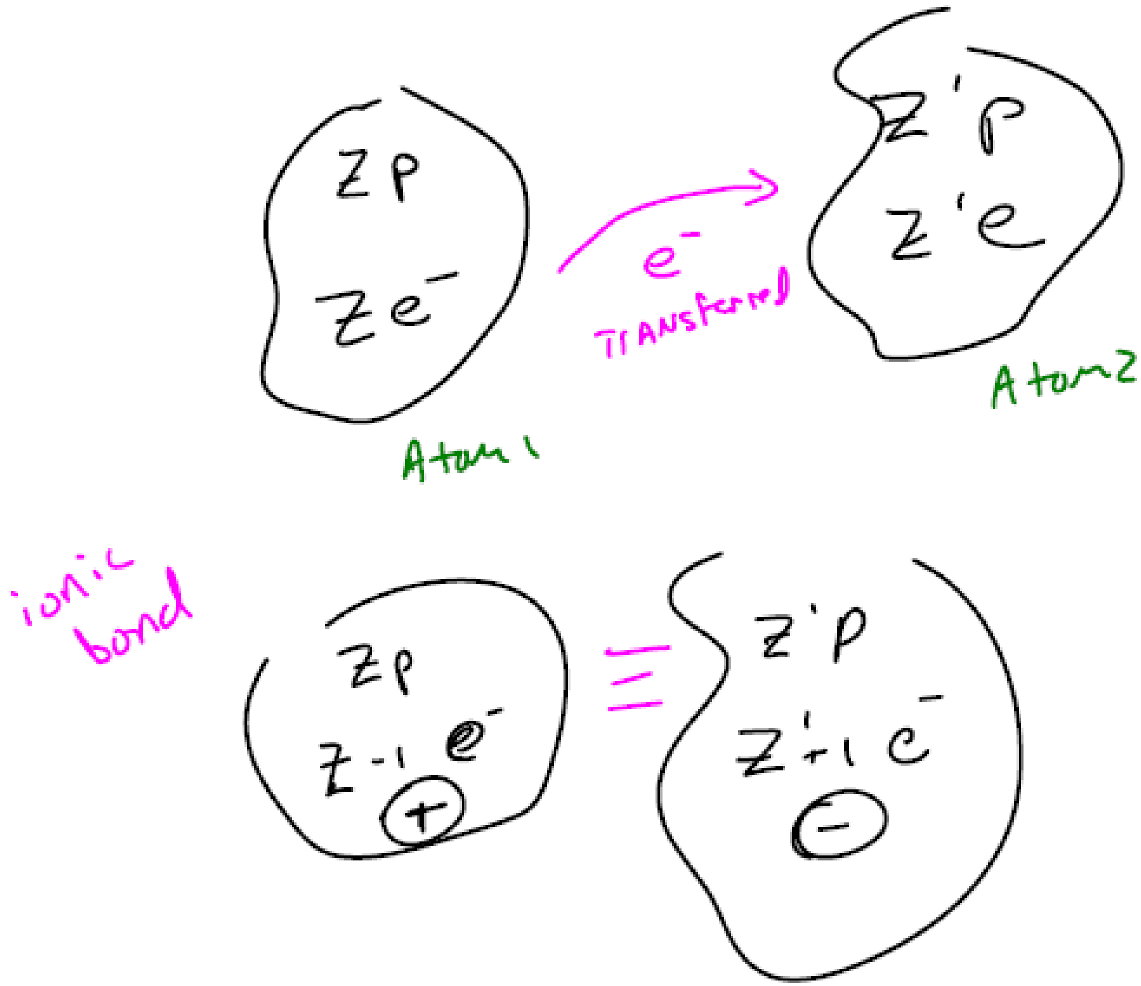

Zp
Ze⁻
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e⁻
transferred
Z'p
Z'e
Atom 2
ionic
bond
Zp
Z-1 e⁻
+
Z'p
Z'+1 e⁻
−


e⁻e⁻
covalent bond