PHOT 222: Quantum Photonics
LECTURE 14

Michaël Barbier, Spring semester (2024-2025)

OVERVIEW OF THE COURSE

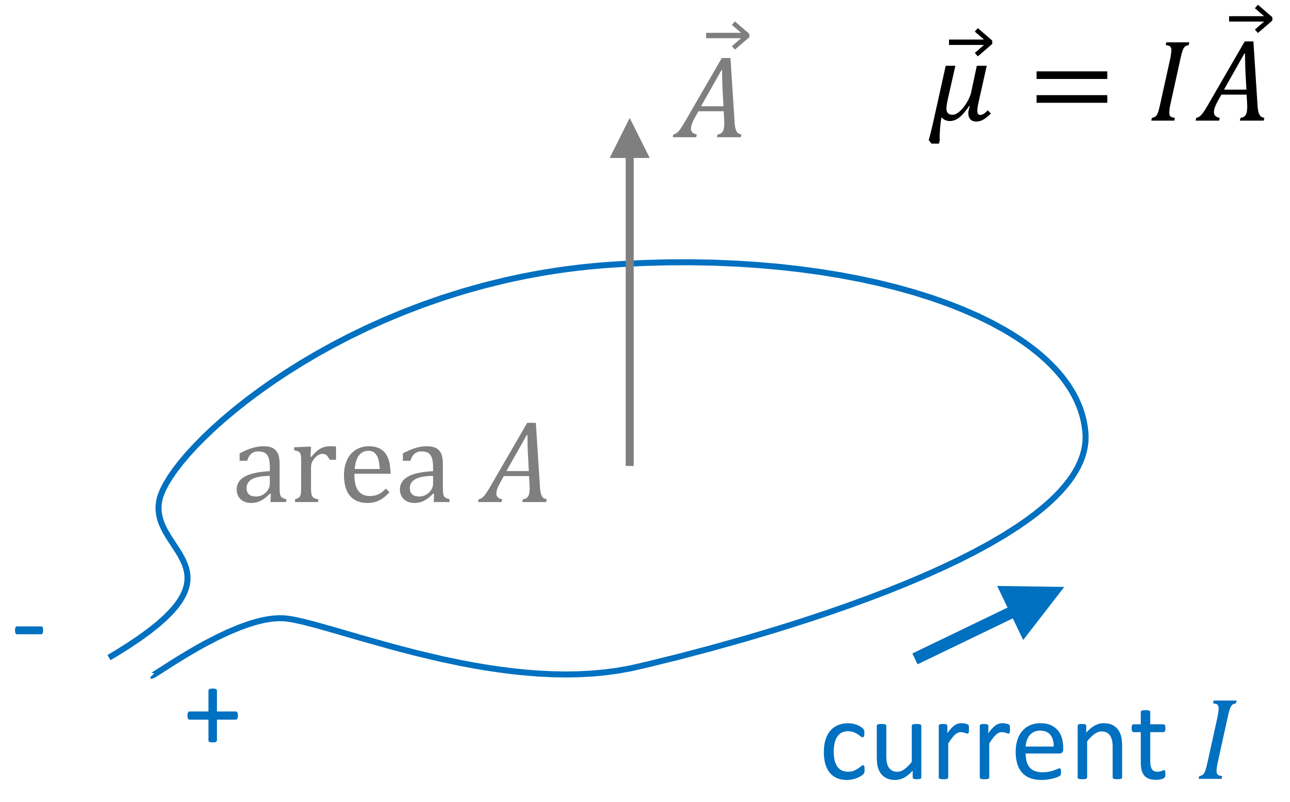
week	topic	Serway 9^{th}	Young
Week 1	Relativity	Ch. 39	Ch. 37
Week 2	Waves and Particles	Ch. 40	Ch. 38-39
Week 3	Wave packets and Uncertainty	Ch. 40	Ch. 38-39
Week 4	The Schrödinger equation and Probability	Ch. 41	Ch. 39
Week 5	**Midterm exam 1**		
Week 6	Quantum particles in a potential	Ch. 41	Ch. 40
Week 7	Bayram		
Week 8	Harmonic oscillator	Ch. 41	Ch. 40
Week 9	Tunneling through a potential barrier	Ch. 41	Ch. 40
Week 10	**Midterm exam 2**		
Week 11	Bohr's hydrogen atom, absorption/emission spectra	Ch. 42	Ch. 41
Week 12	Quantum mechanical model of the hydrogen atom	Ch. 42	Ch. 41
Week 14	**Spin / Many-electron atoms**	**Ch. 42**	**Ch. 41**
Week 14	Molecules, Crystalline materials & energy band structure	Ch. 43	Ch. 42

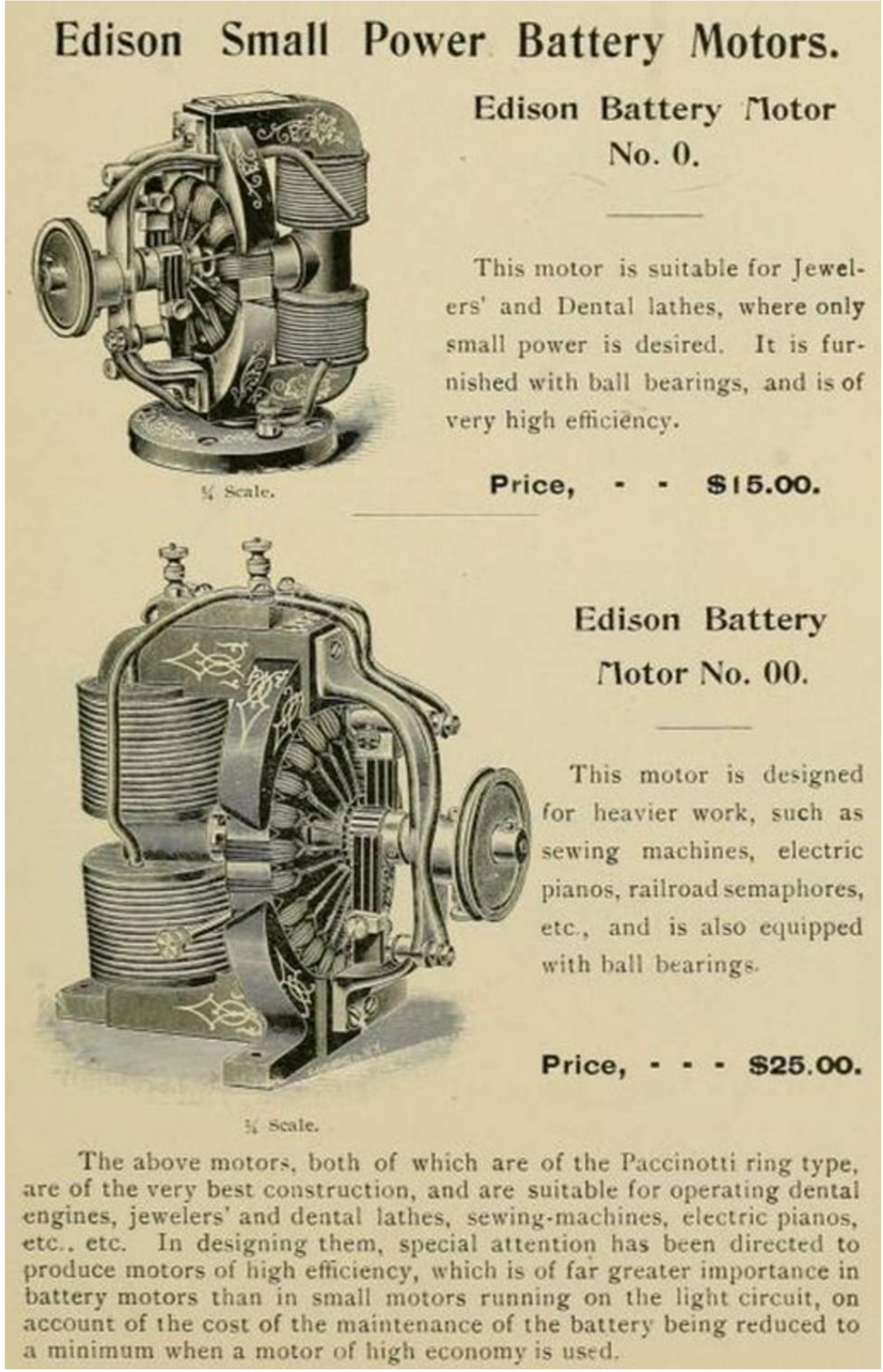
Normal Zeeman Effect: Applying a Magnetic Field

MAGNETIC MOMENT BY CURRENT

- Current around an area creates a magnetic field
  - **Magnetic dipole moment**: $\vec{\mu} = I\vec{A}$
  - Depends on the current/charge
  - Current is charge per time: $I = \frac{e}{T}$

1897 Thomas Edison "O"
Bipolar Utility Motor





Edison Small Power Battery Motors.

Edison Battery Motor No. 0.

This motor is suitable for Jewelers' and Dental lathes, where only small power is desired. It is furnished with ball bearings, and is of very high efficiency.

½ Scale.

Price, - - $15.00.

Edison Battery Motor No. 00.

This motor is designed for heavier work, such as sewing machines, electric pianos, railroad semaphores, etc., and is also equipped with ball bearings.

Price, - - - $25.00.

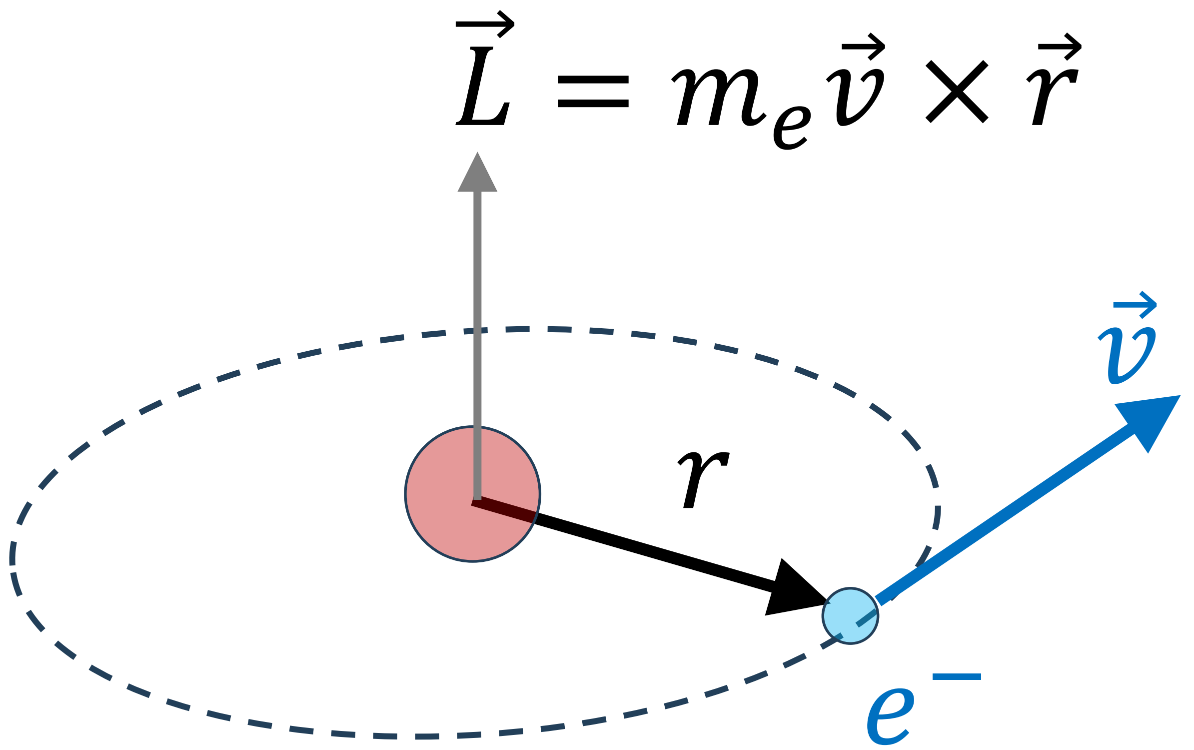
½ Scale.

The above motors, both of which are of the Paccinotti ring type, are of the very best construction, and are suitable for operating dental engines, jewelers' and dental lathes, sewing-machines, electric pianos, etc., etc. In designing them, special attention has been directed to produce motors of high efficiency, which is of far greater importance in battery motors than in small motors running on the light circuit, on account of the cost of the maintenance of the battery being reduced to a minimum when a motor of high economy is used.

MAGNETIC MOMENT OF AN ORBITING ELECTRON

- Bohr: electron going along an orbit
  - Angular momentum: $\vec{L} = m_e \vec{v} \times \vec{r}$
  - **Magnetic dipole moment**: $\vec{\mu} = I\vec{A}$
  - Current is charge per time: $I = \frac{e}{T}$

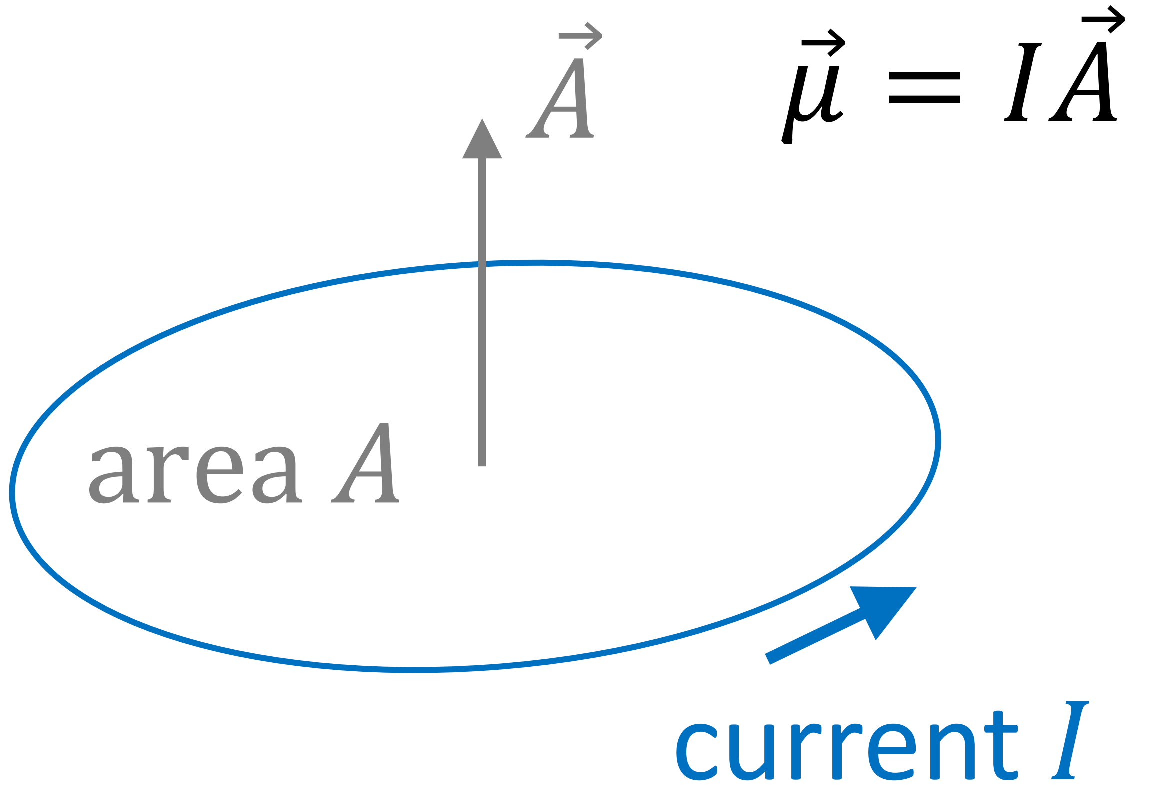
$$\Rightarrow \mu = IA = \frac{e\ v}{2\pi r} \cdot \pi r^2 = \frac{evr}{2}$$



- Substitute $L = m_e vr$

$$\Rightarrow \mu = \frac{evr}{2} = \frac{e}{2m_e} L$$

with **gyromagnetic ratio**: $\frac{\mu}{L} = \frac{e}{2m_e}$



MAGNETIC FIELD APPLIED TO AN ORBITING ELECTRON

- Magnetic dipole moment: $\vec{\mu} = -\frac{e\vec{L}}{2m_e}$

- dipole $\vec{\mu}$ in magnetic field $\vec{B}$ undergoes torque $\vec{\tau} = \vec{\mu} \times \vec{B}$

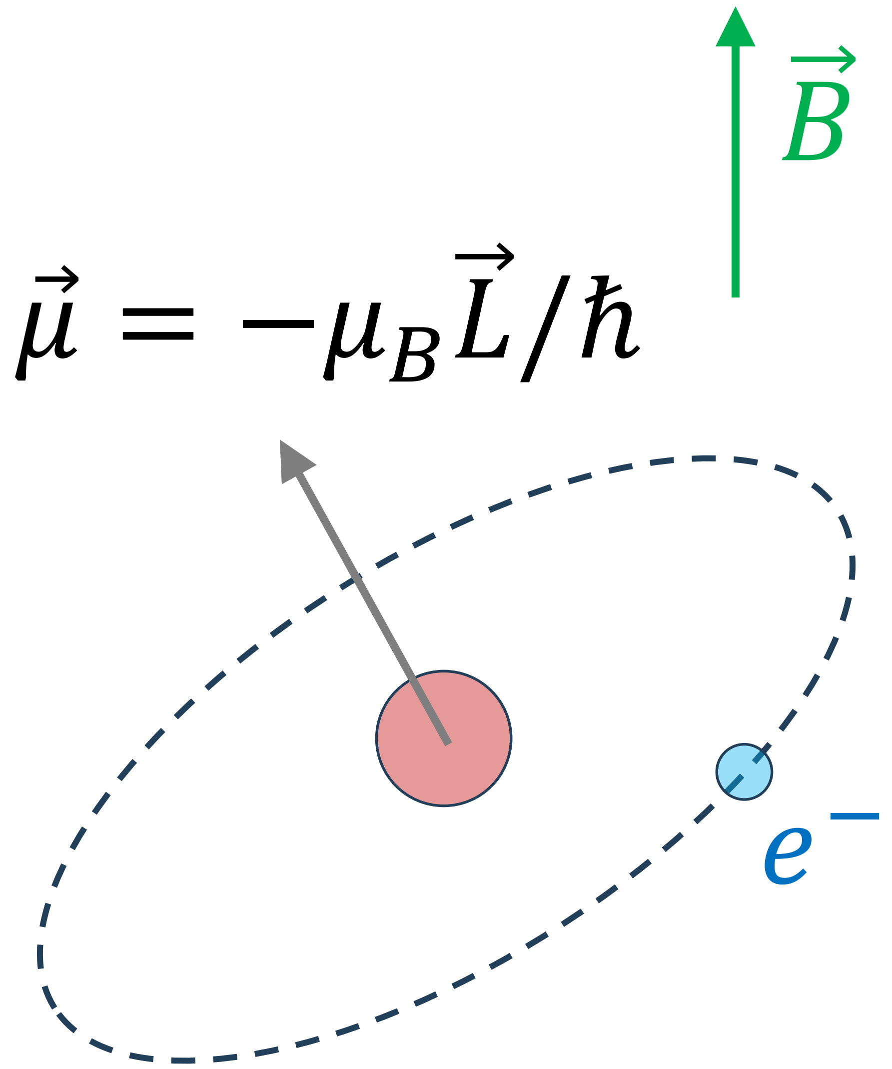
$$\Rightarrow \quad U = -\vec{\mu} \cdot \vec{B}$$

- In the ground state the Bohr model has $L = n\hbar = \hbar$ giving a nonzero magnetic moment

$$\mu = \frac{eL}{2m_e} = \frac{e\hbar}{2m_e} = \mu_B \Leftarrow$$

Bohr magneton $\mu_B = 5.788 \times 10^{-5} \frac{eV}{T}$

- According to Schrodinger's equation:
  - Electron in s-state with zero angular momentum?



APPLYING A MAGNETIC FIELD

- Quantum Mechanics:
  - Quantized angular momentum: $\vec{L} = \sqrt{l(l+1)}\hbar$
  - Magnetic quantum number: $L_z = m_l\hbar$

- Gyromagnetic ratio $\frac{\mu}{L} = \frac{e}{2m_e}$ still valid
- Magnetic field along z-axis: $U = -\vec{\mu}\cdot\vec{B} = -\mu_z B$

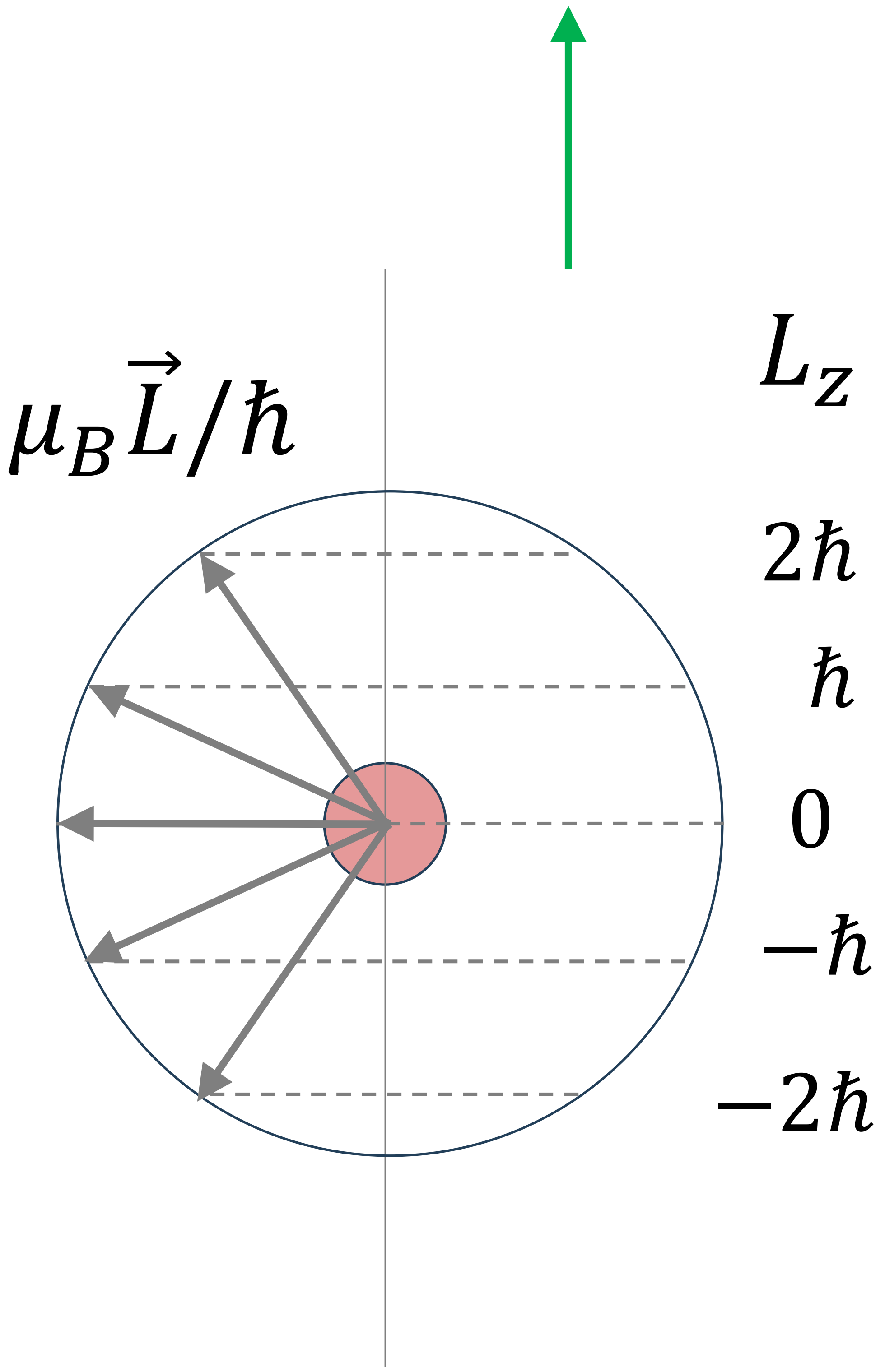
- Magnetic moment quantized:

$$\mu_z = -\frac{e}{2m_e}L_z = -m_l\frac{e\hbar}{2m_e} = -m_l\mu_B$$

$$\Rightarrow \quad U = -\mu_z B = m_l\mu_B B$$

$\vec{B} = B\vec{e}_z$

$\vec{\mu} = -\mu_B\vec{L}/\hbar$



APPLYING A MAGNETIC FIELD

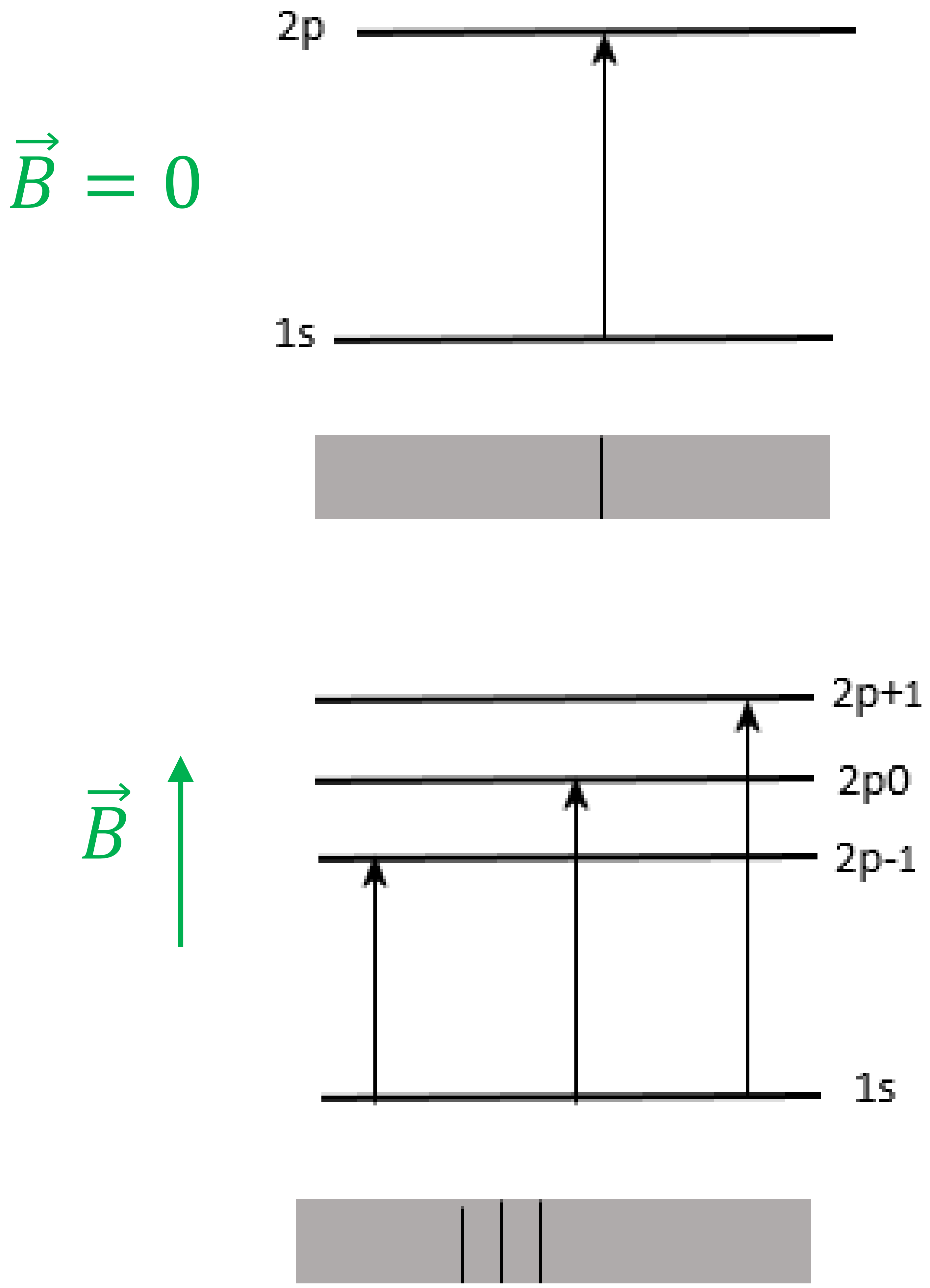
- No magnetic field: Energy depends only on quantum number n:

$$E_n = -\frac{Z^2}{n^2} \cdot 13.6\ \text{eV}$$

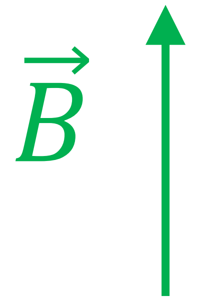
- Magnetic field B results $E_n \rightarrow E_n + U_B$:

$$E_n = E_n + m_l \mu_B B \quad \text{with} \quad m_l = -l, \dots, l$$

- **Normal Zeeman effect**: splitting E_n in $2n - 1$ levels
- The splitting scales with magnetic field B



APPLYING A MAGNETIC FIELD



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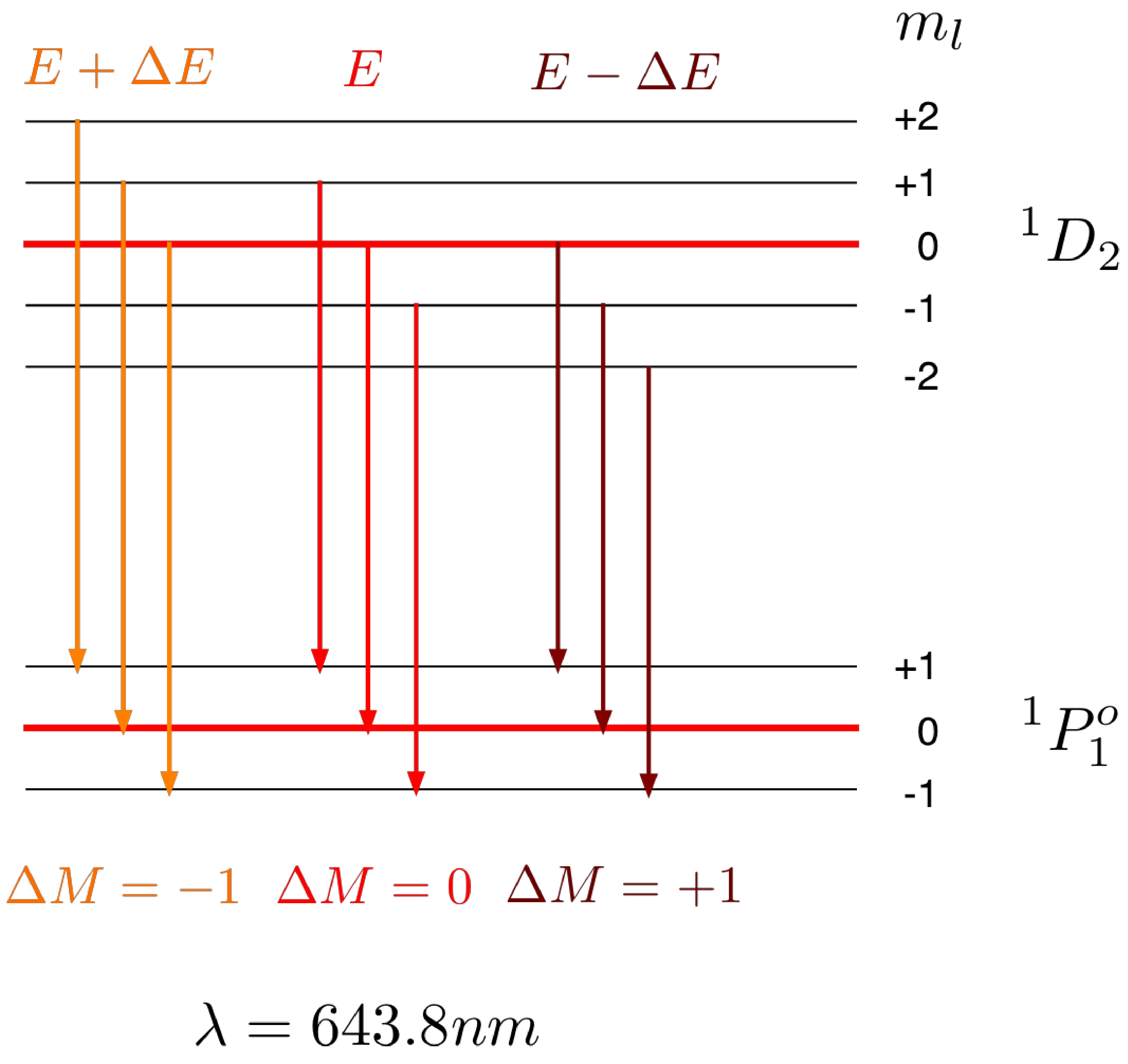
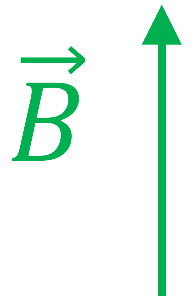
- **Normal Zeeman effect**: splitting E_n in $2n - 1$ levels
- The splitting scales with magnetic field B
- Spectral lines split according **selection rules**



Adapted from the course of Werner Boeglin

SELECTION RULES



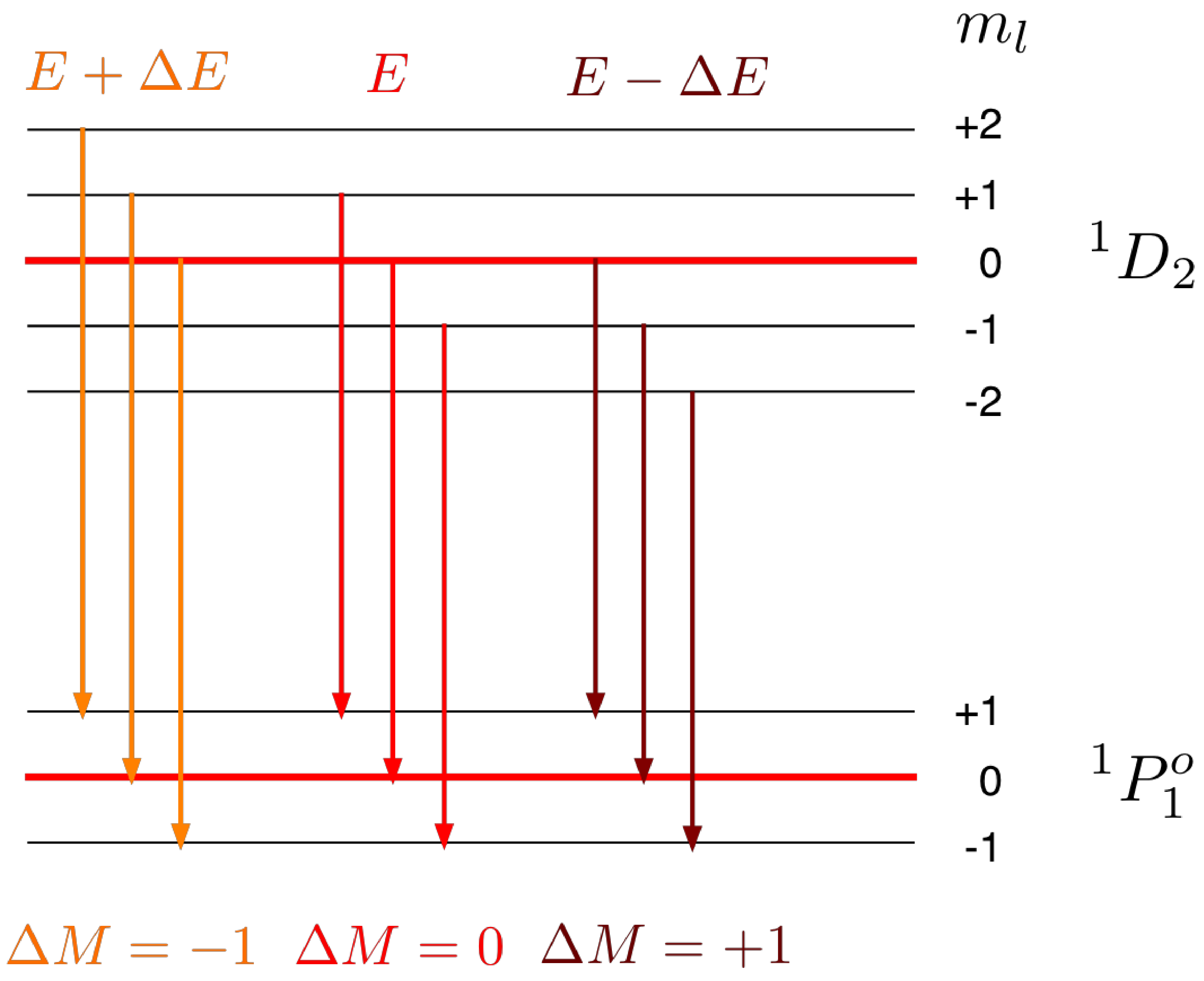
$$E_n = E_n + m_l \mu_B B \quad \text{with} \quad m_l = -l, \dots, l$$

- Angular momentum should be conserved
- A photon uses one unit $\hbar$ of angular momentum
- Selection rules:

1. Orbital quantum number $l \rightarrow l - 1$
2. Magnetic quantum number:

$$m_l \rightarrow m_l \pm 1 \quad \text{or} \quad m_l \rightarrow m_l$$

Allowed & forbidden transitions

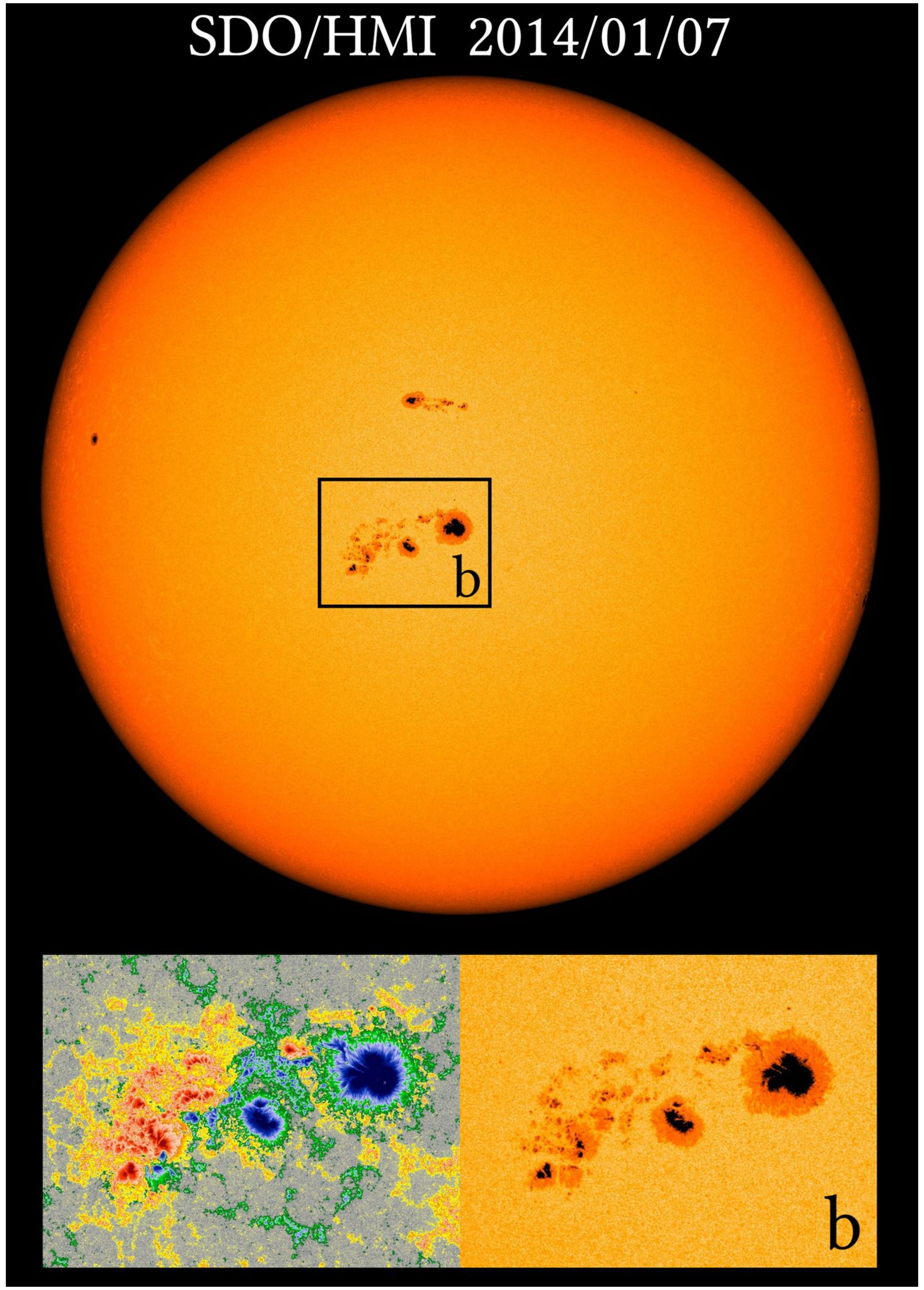


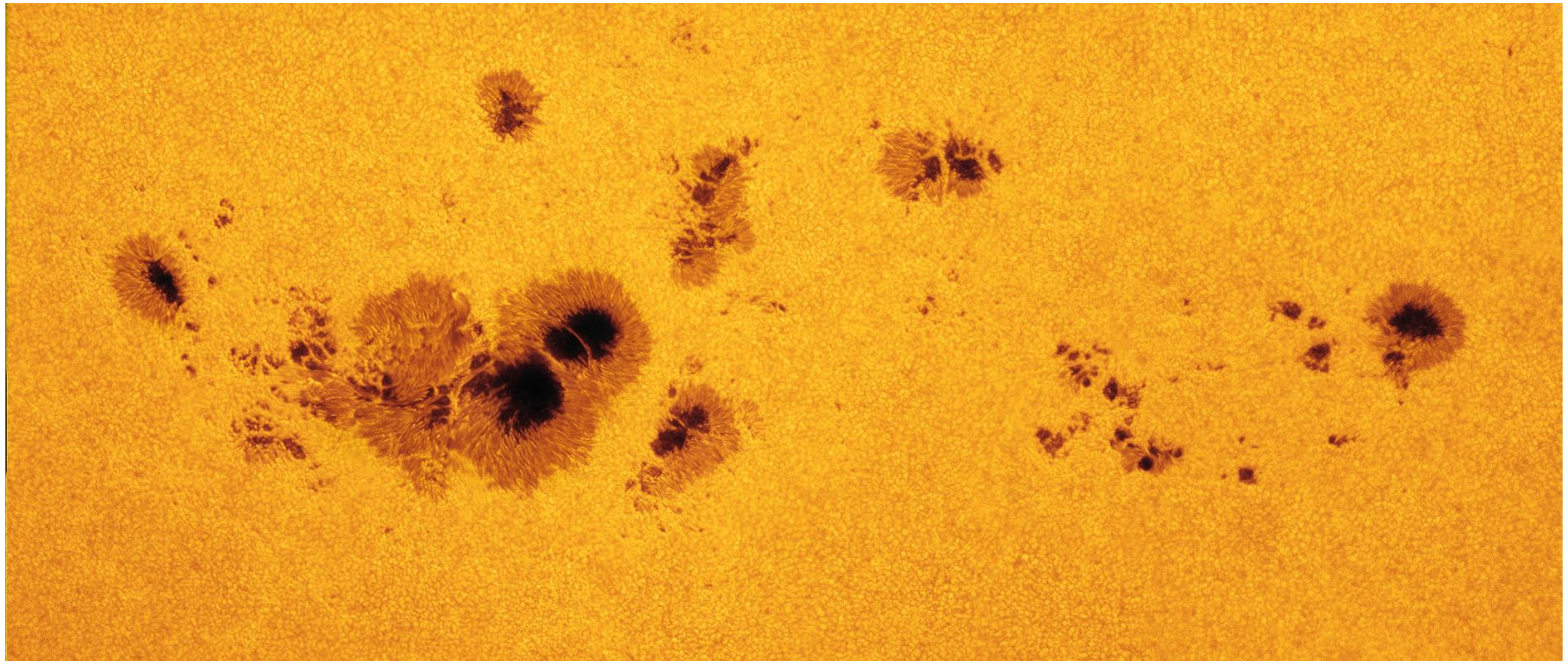
$$\lambda = 643.8nm$$

Adapted from the course of Werner Boeglin

EXAMPLE NORMAL ZEEMAN SPLITTING: SOLAR SPOTS

- Solar spots are regions in the sun:
  - Lower in temperature (3000-4500 K vs 5800 K)
  - Move around the sun in time, towards the equator

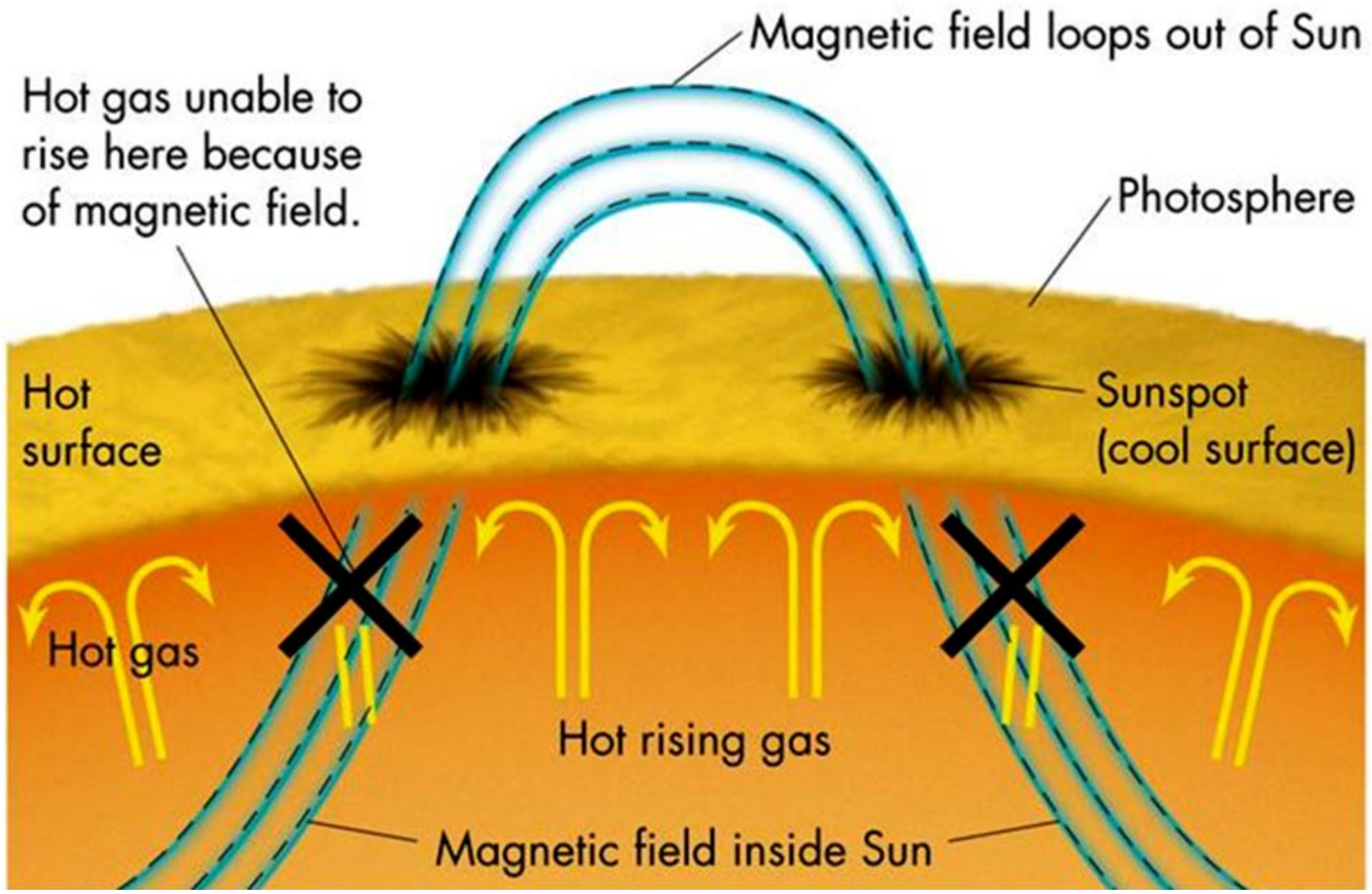




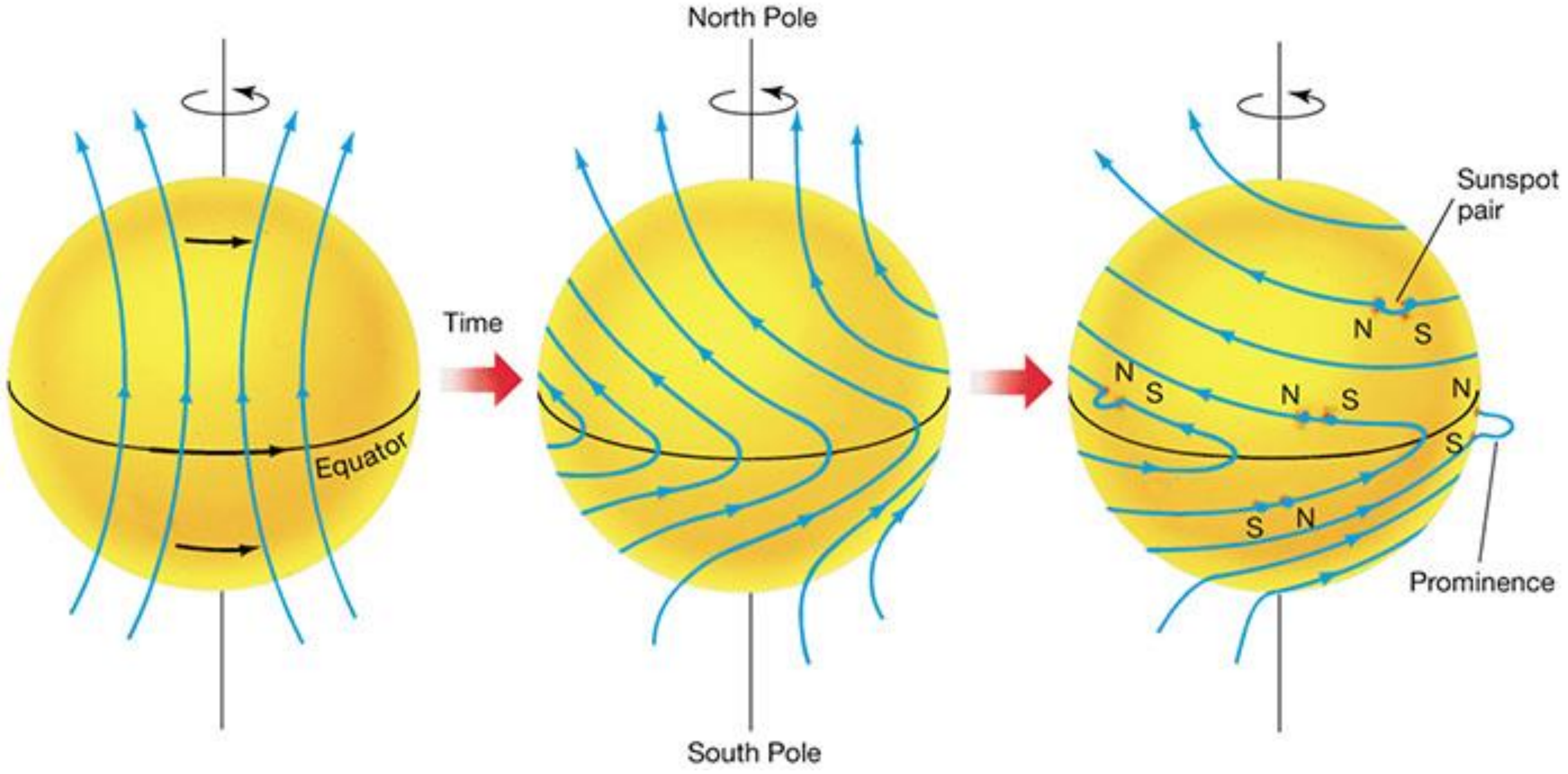
Adapted from Wikipedia, Original image taken by Alan Friedman in 2012.

EXAMPLE NORMAL ZEEMAN SPLITTING: SOLAR SPOTS

- Solar spots are regions in the sun:
    - Lower in temperature (3000-4500 K vs 5800 K)
    - High magnetic flux density



Adapted from “Spots on the Sun”, article at cosmosatyourdoorstep.com

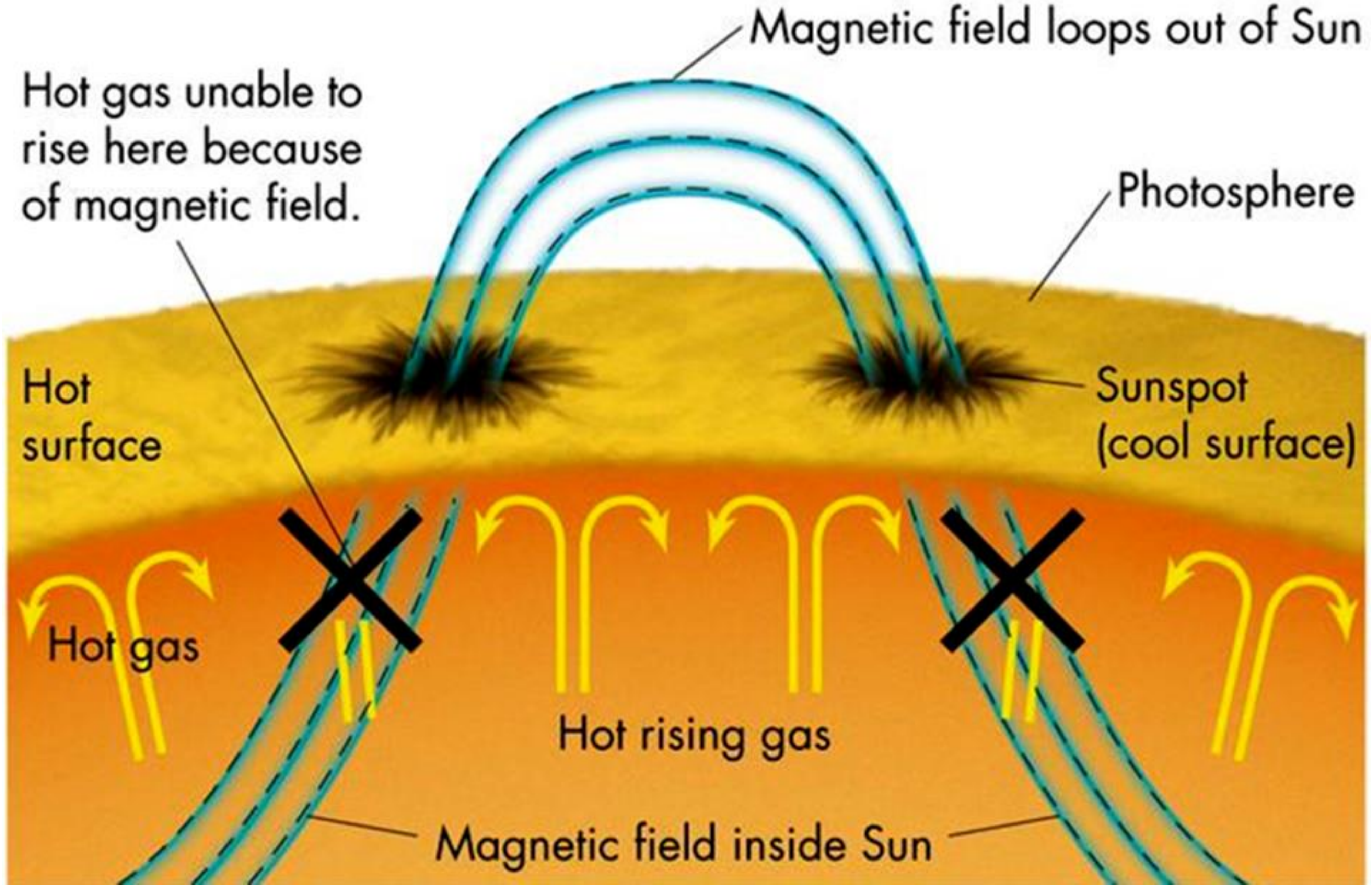


EXAMPLE NORMAL ZEEMAN SPLITTING: SOLAR SPOTS

- Measure magnetic field by the Zeeman effect

Zeeman splitting
(B = 0.41 Tesla)

Fe line at 525 nm



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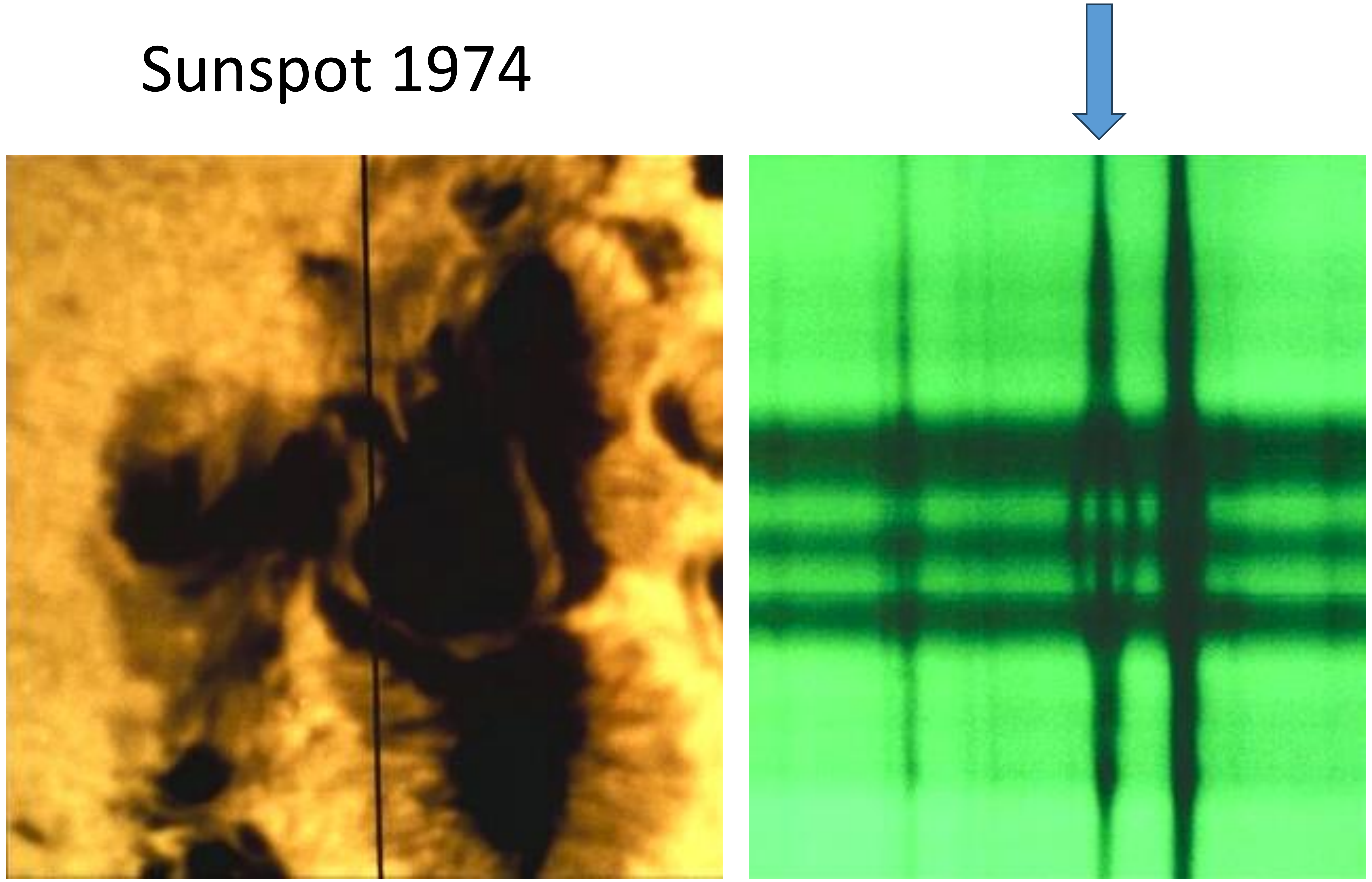
Sunspot 1974

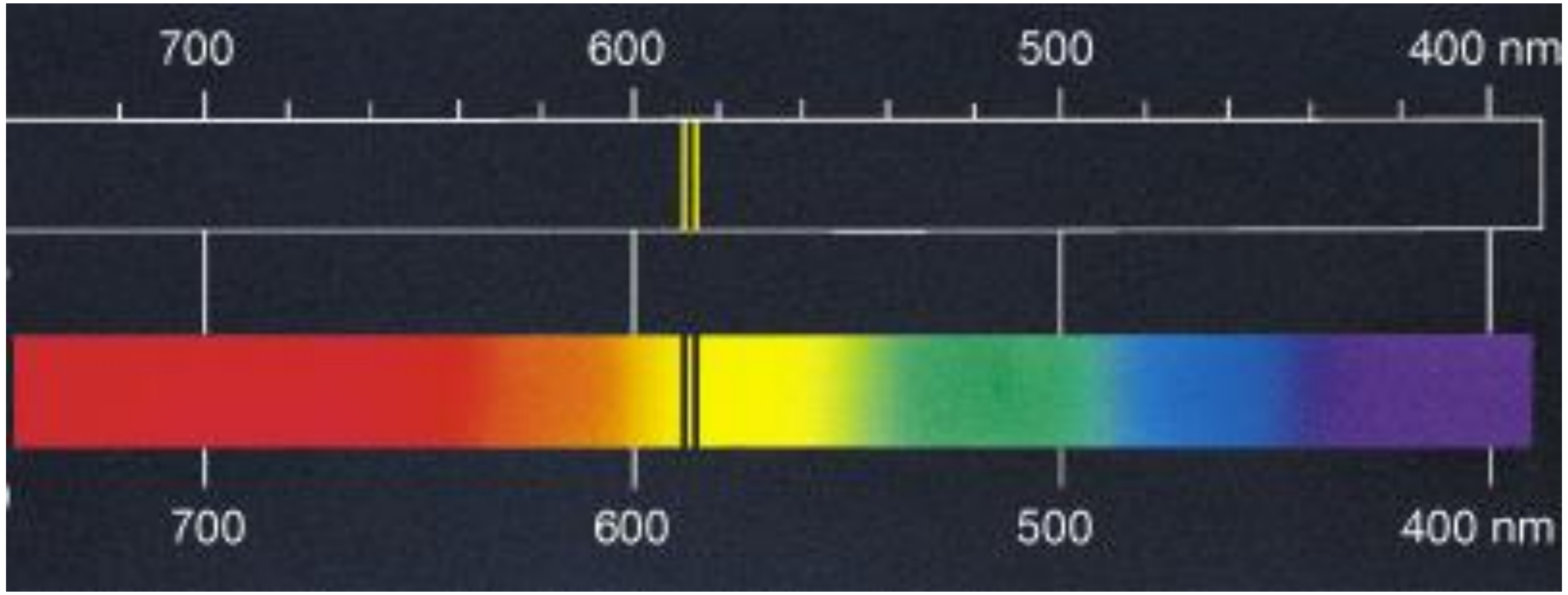


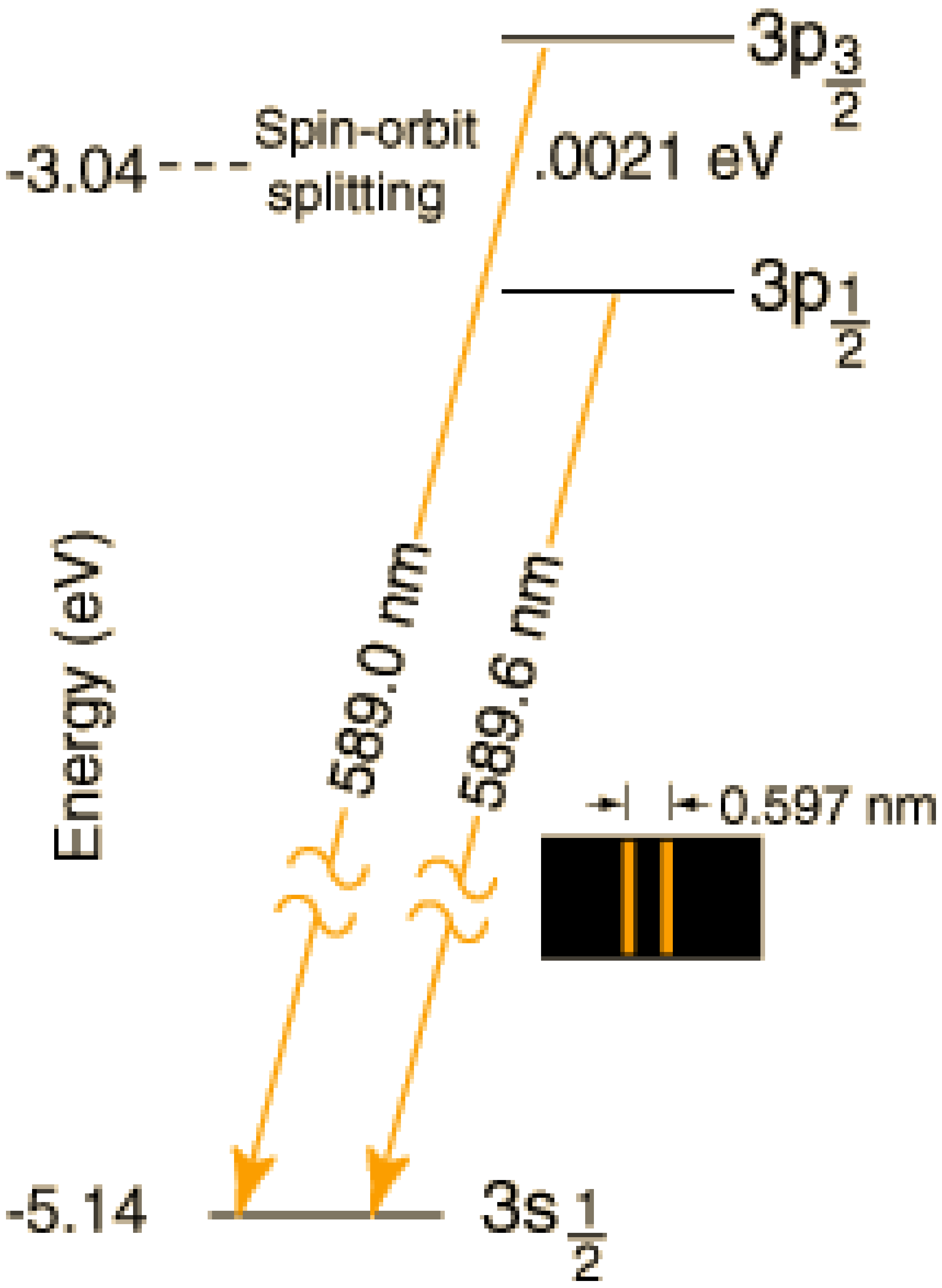
Adapted from NOIRLab, picture taken at McMath-Pierce Solar Facility on Kitt Peak.

Electron Spin

THE SODIUM DOUBLET LINE

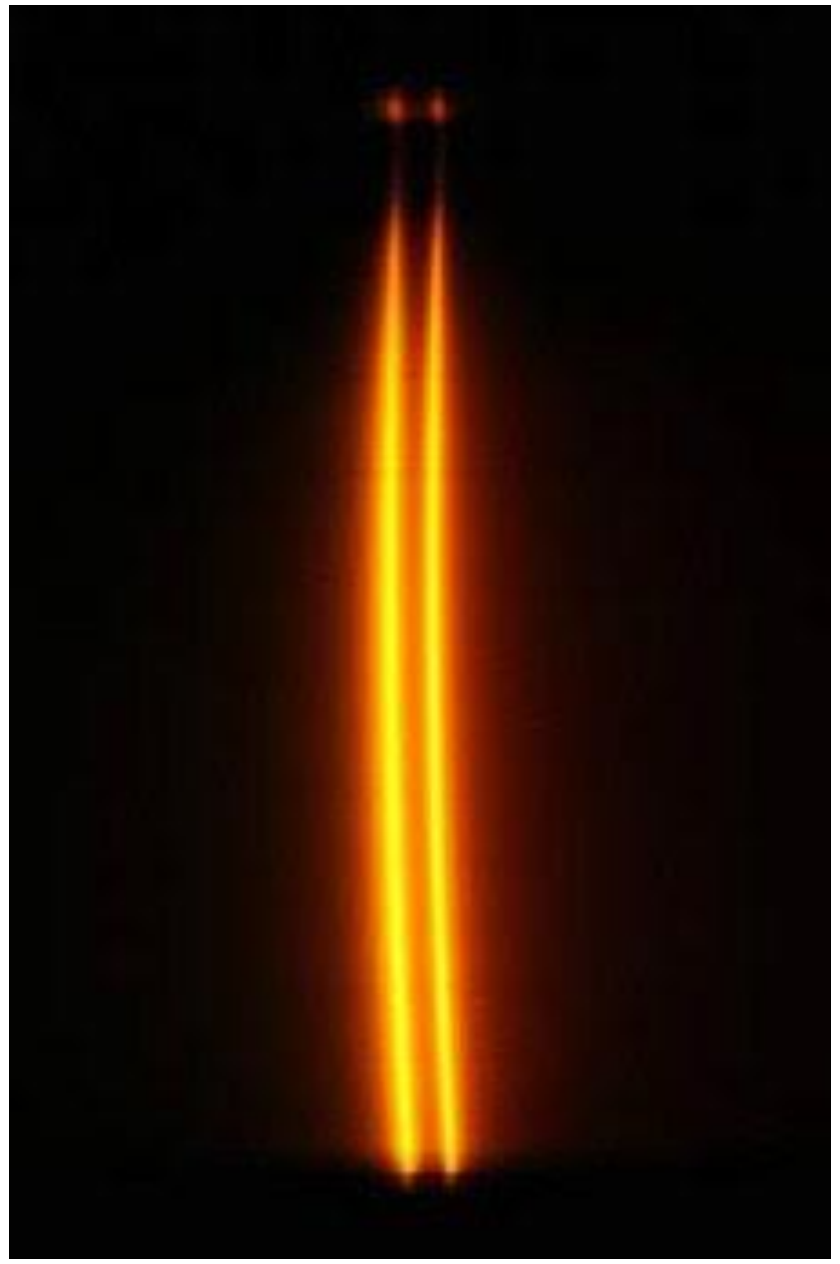
- Spectrum Sodium (Na) doublet line
- Transition: 3p → 3s
- Effect of electron spin splits a single orbital in two energy-levels

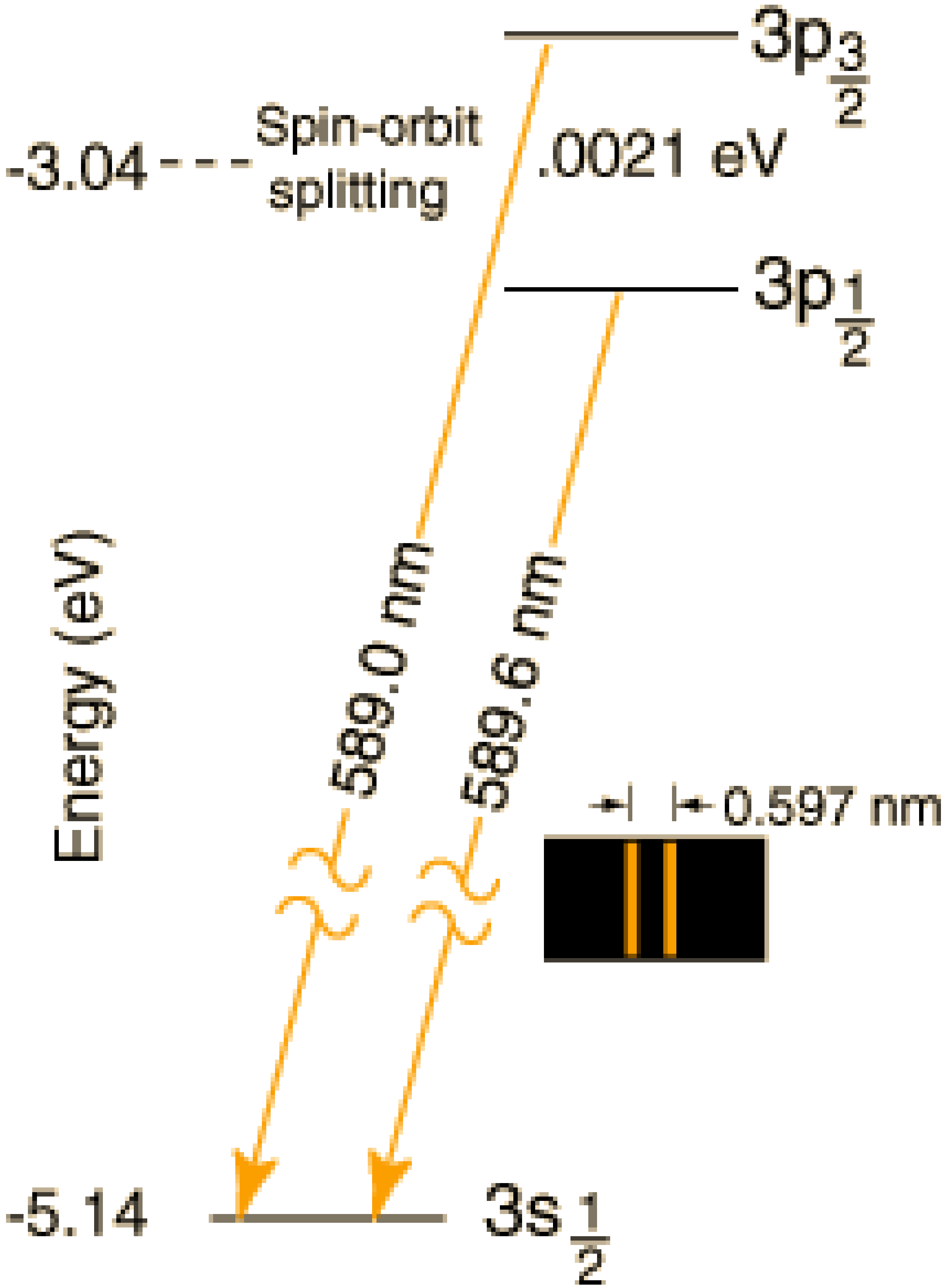




THE SODIUM DOUBLET LINE

- Spectrum Sodium (Na) doublet line
- What is the reason for this small energy difference?

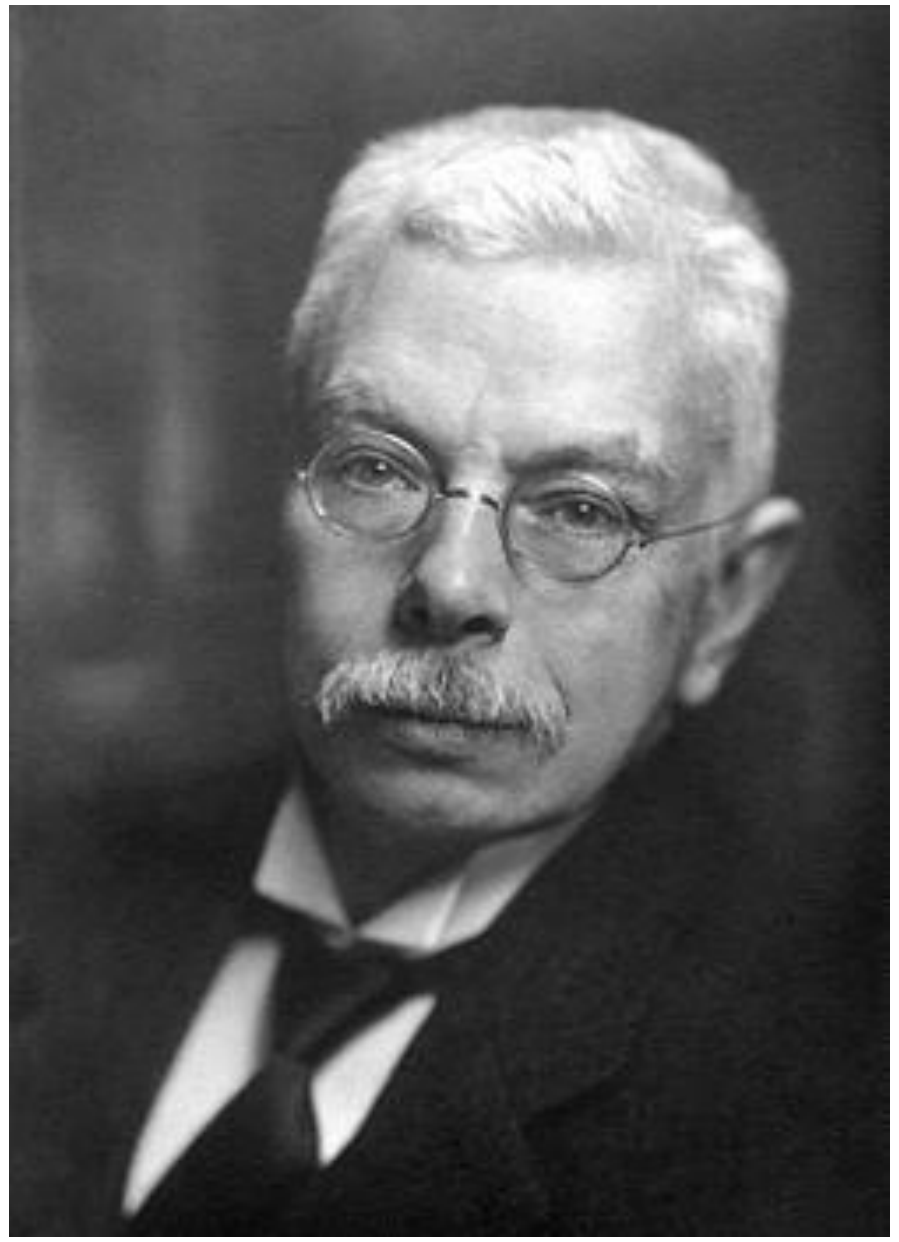




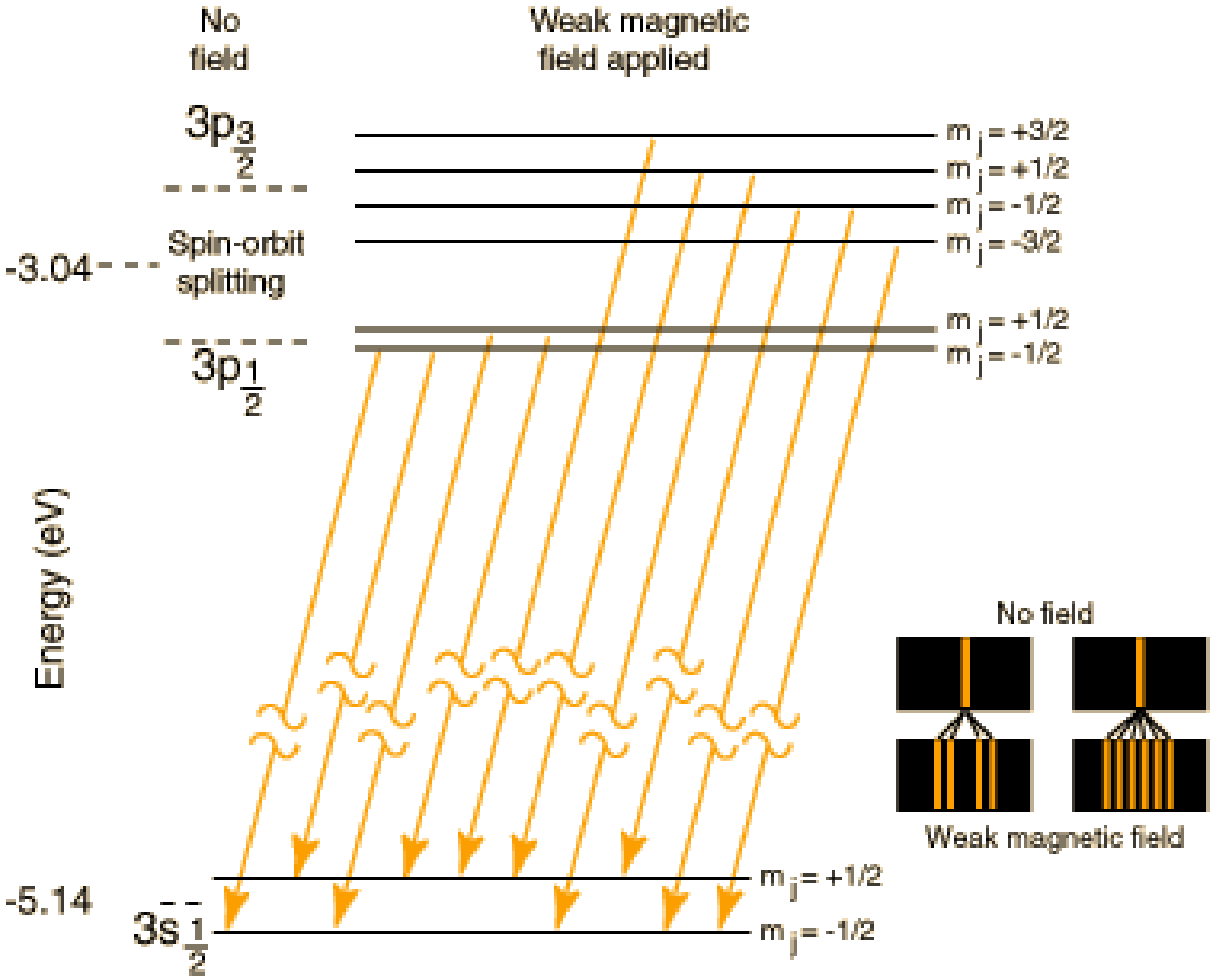
THE ANOMALOUS ZEEMAN SPLITTING

- **1896**: **Zeeman splitting** of Sodium doublet line by magnetic field

(electron not yet discovered)



Pieter Zeeman



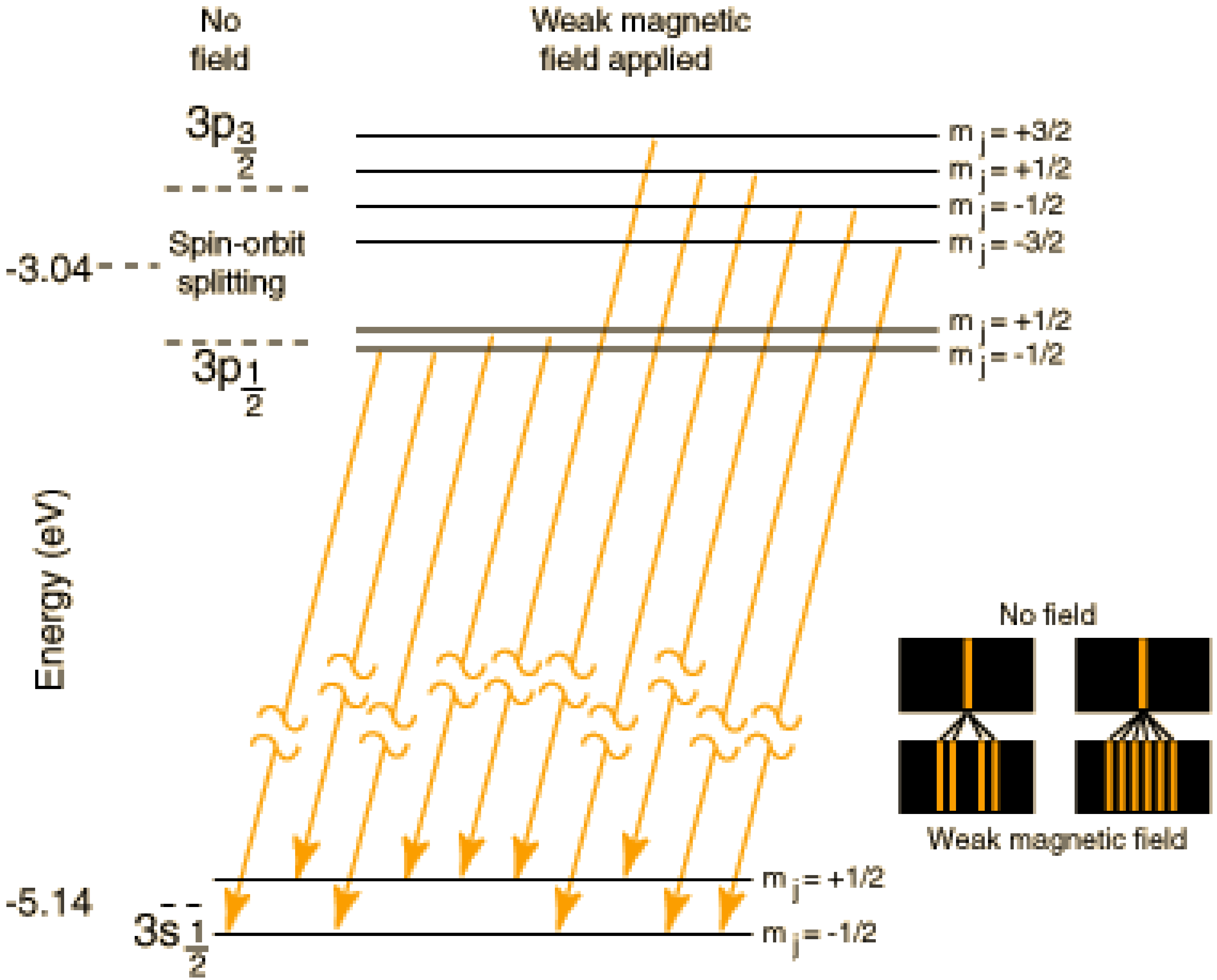
THE ANOMALOUS ZEEMAN SPLITTING

- **1896**: **Zeeman splitting** of Sodium doublet line by magnetic field

(electron not yet discovered)

- No logical explanation when using only quantum numbers n, l, m_l?

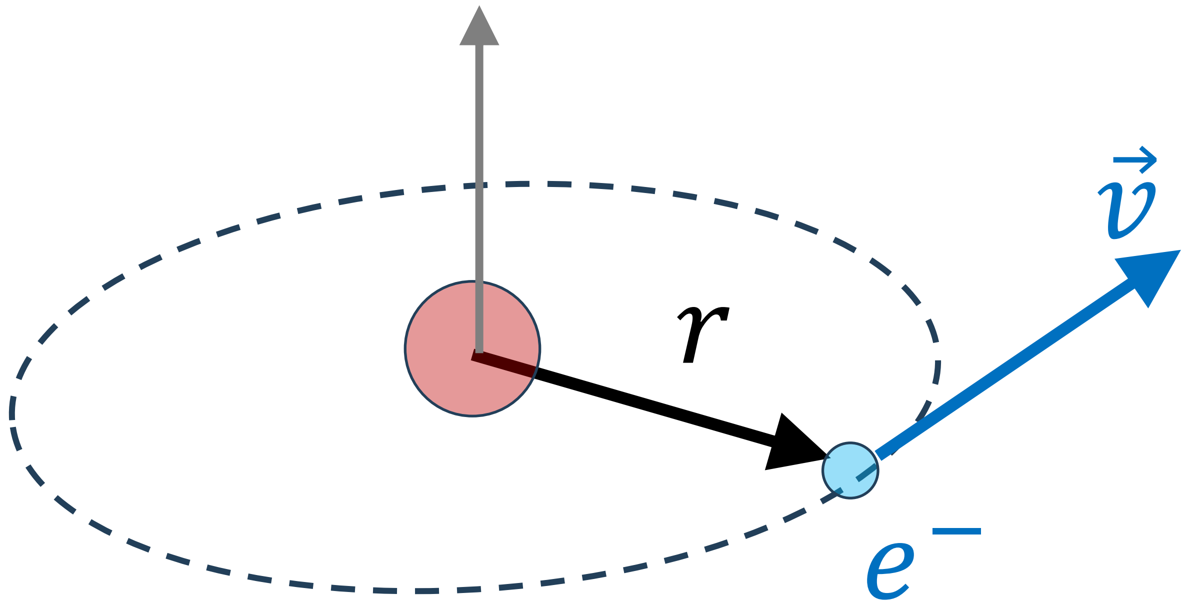
- Solution: extra quantum number - **spin magnetic quantum number**



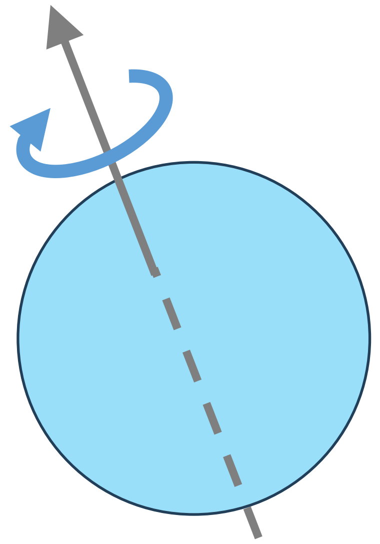
THE IDEA OF SPIN

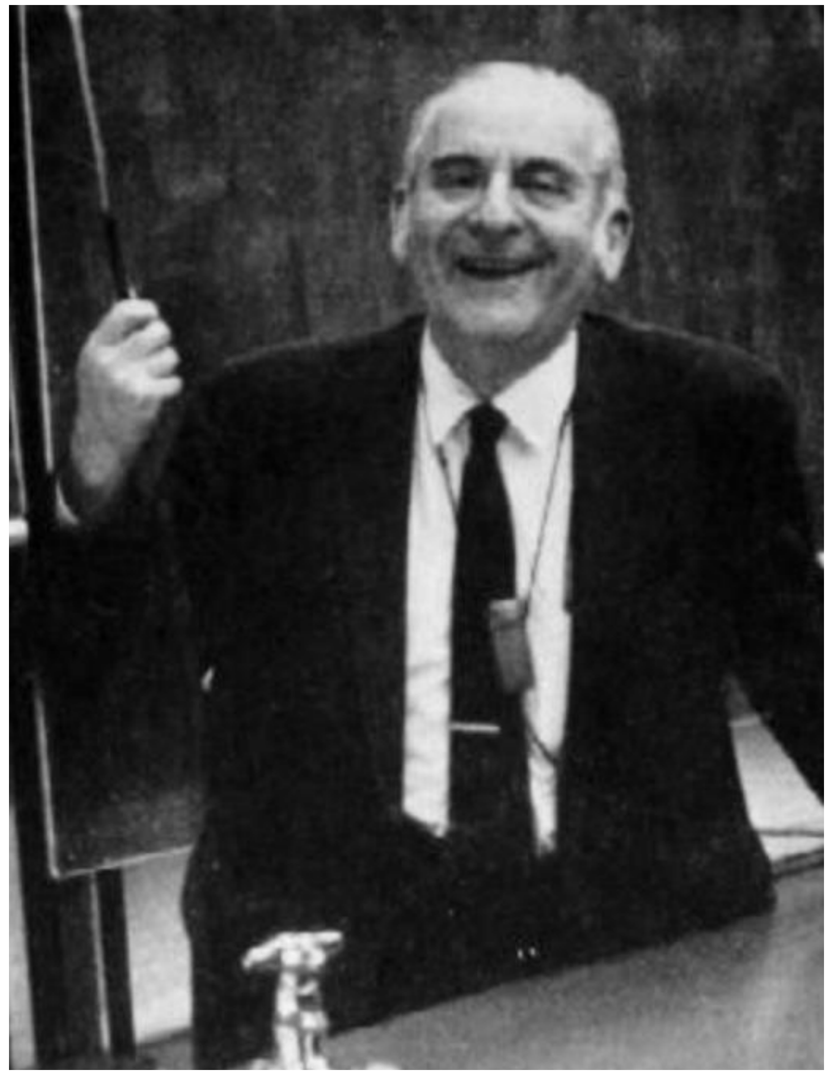
- The Schrodinger equation does not predict spin
- **1925**: Goudsmit & Uhlenbeck propose extra quantum number m_s
- Analogy of spinning Earth? No …

$$\vec{L} = m_e \vec{v} \times \vec{r}$$

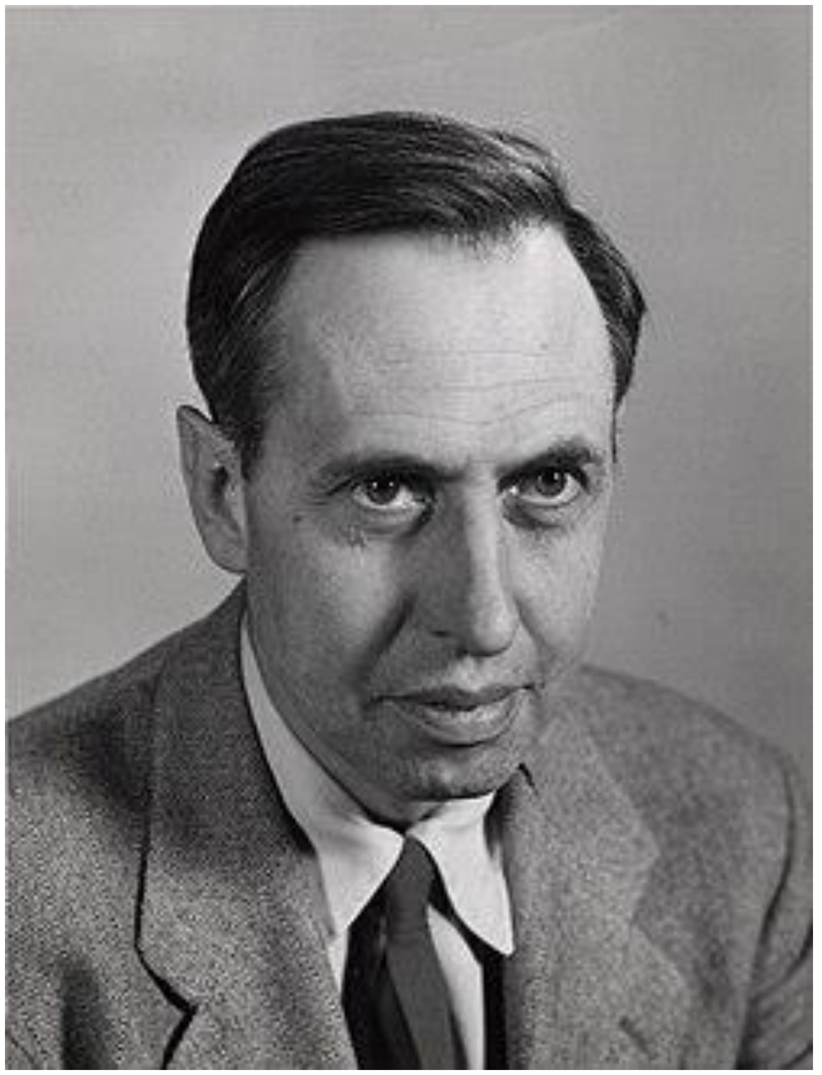


$$\vec{S}$$





Samuel Goudsmit



George Uhlenbeck

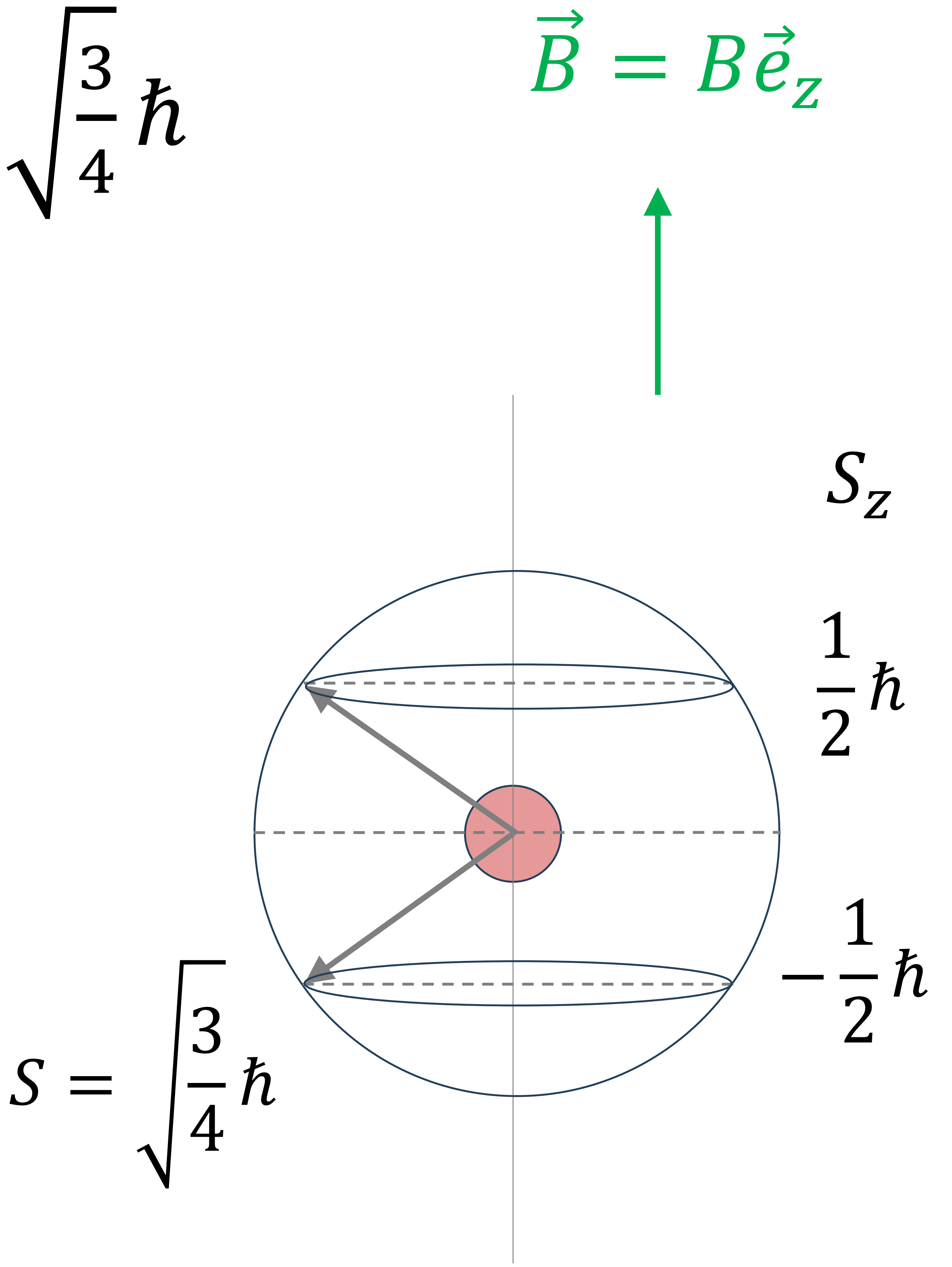
Wolfgang Pauli

THE IDEA OF SPIN

- Similar to analysis of angular momentum:
- Magnitude of spin: $$S = \sqrt{\frac{1}{2}\left(\frac{1}{2} + 1\right)}\,\hbar = \sqrt{\frac{3}{4}}\,\hbar$$
- Spin quantum number: $$S_z = m_s\hbar = \pm\frac{1}{2}\hbar$$
- Spin magnetic moment:

$$\mu_z = -\frac{(2.0023)\mu_B S_z}{\hbar} \approx -\frac{2\mu_B S_z}{\hbar}$$

- Spin will just as the angular momentum contribute to a magnetic moment



TOTAL ANGULAR MOMENTUM J

- The **total angular momentum**: $\vec{J} = \vec{L} + \vec{S}$
- Magnitude total angular momentum: $J = \sqrt{j(j+1)}\,\hbar$

Orbital magnetic quantum number: $m_l = -l, \dots, -1, 0, 1, \dots, l$

Spin magnetic quantum number: $m_s = -s, \dots, -\frac{1}{2}, \frac{1}{2}, \dots, s$

Total angular momentum quantum number: $m_j = -j, \dots, j$

$$m_j = m_l + m_s$$

Notation for orbitals :

n m_l

$2p_{-1}$

$l \equiv s, p, d, f, \dots$

m_j

$2P_{\frac{3}{2}}$

l now capital letter

FINE STRUCTURE OF THE HYDROGEN ATOM

- Magnetic moments originating from electron orbit and spin:

$$\mu_z = -\frac{\mu_B L_z}{\hbar} \quad \text{and} \quad \mu_{z,\text{spin}} \approx -\frac{2\mu_B S_z}{\hbar}$$

- Magnetic moments lead to potential energy contributions
- Energy depends not only on n but also on j:

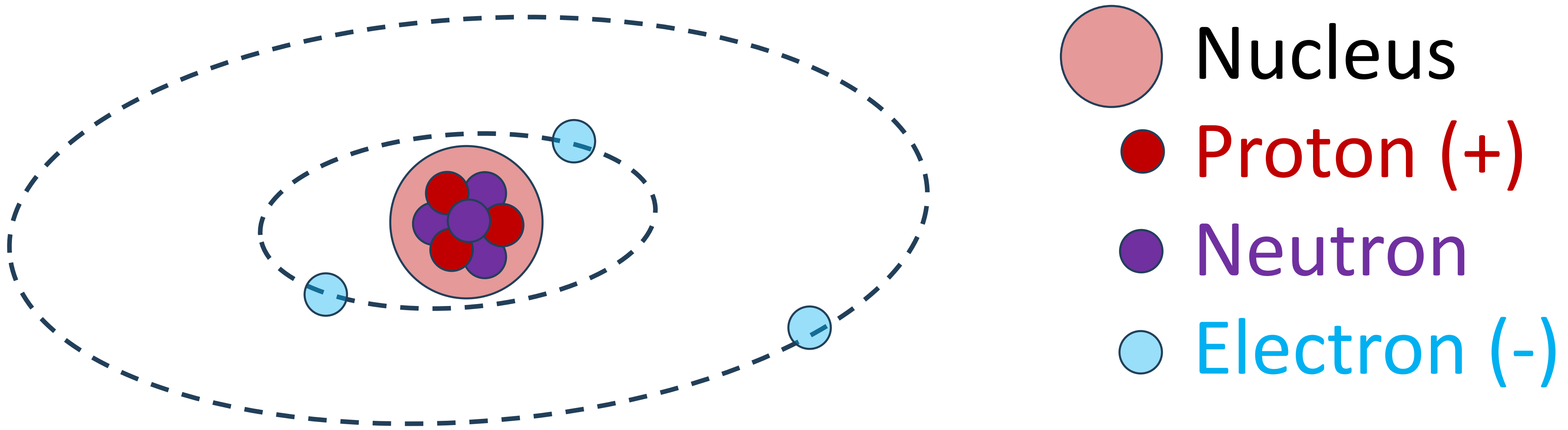
$$E_{n,j} = -\frac{13.6\ \text{eV}}{n^2} \times \left[1 + \frac{\alpha^2}{n^2}\left(\frac{n}{j+\frac{1}{2}} - \frac{3}{4}\right)\right]$$

- The **fine structure constant** $\alpha = \frac{1}{4\pi\epsilon_0}\frac{e^2}{\hbar c} \approx 7.297 \times 10^{-3} \approx \frac{1}{137}$

Many Electron Atoms

MULTI-ELECTRON ATOMS

- Atoms with higher atom numbers have more electrons and protons
- Number of protons gives the atom number Z
- The weight of the atom can be larger as protons are “separated” by neutrons



- The multiple electrons fill up possible orbitals
- **1869:** Periodic table of Mendeljeev
  - Elements ordered in 8 groups

ELEMENTS

	Wt		Wt
Hydrogen	1	Strontian	46
Azote	5	Barytes	68
Carbon	54	Iron	50
Oxygen	7	Zinc	56
Phosphorus	9	Copper	56
Sulphur	13	Lead	90
Magnesia	20	Silver	190
Lime	24	Gold	190
Soda	28	Platina	190
Potash	42	Mercury	167

1806: John Dalton, ordering of atoms according to weight

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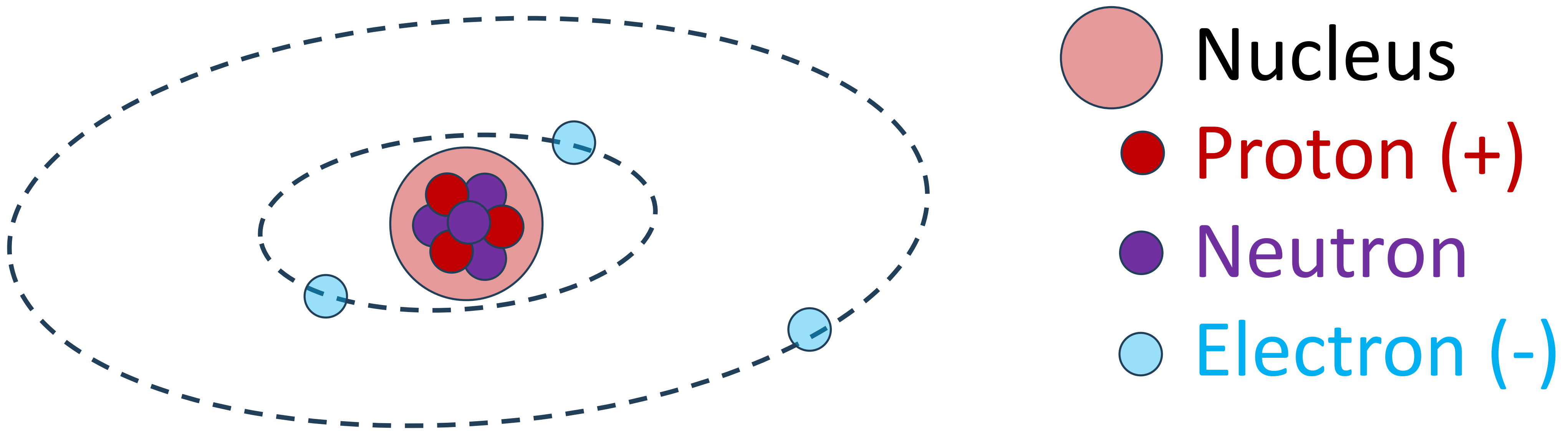

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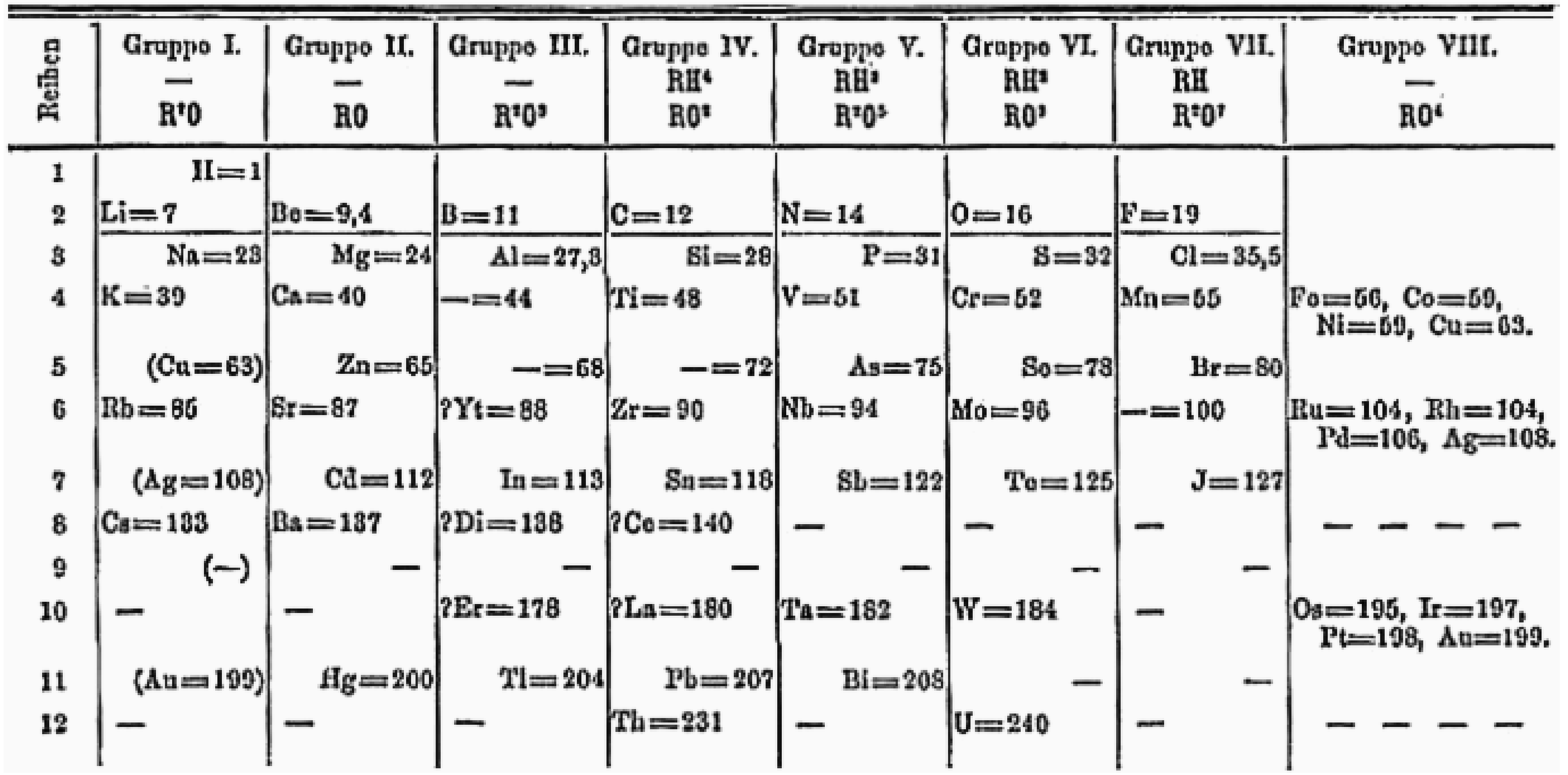


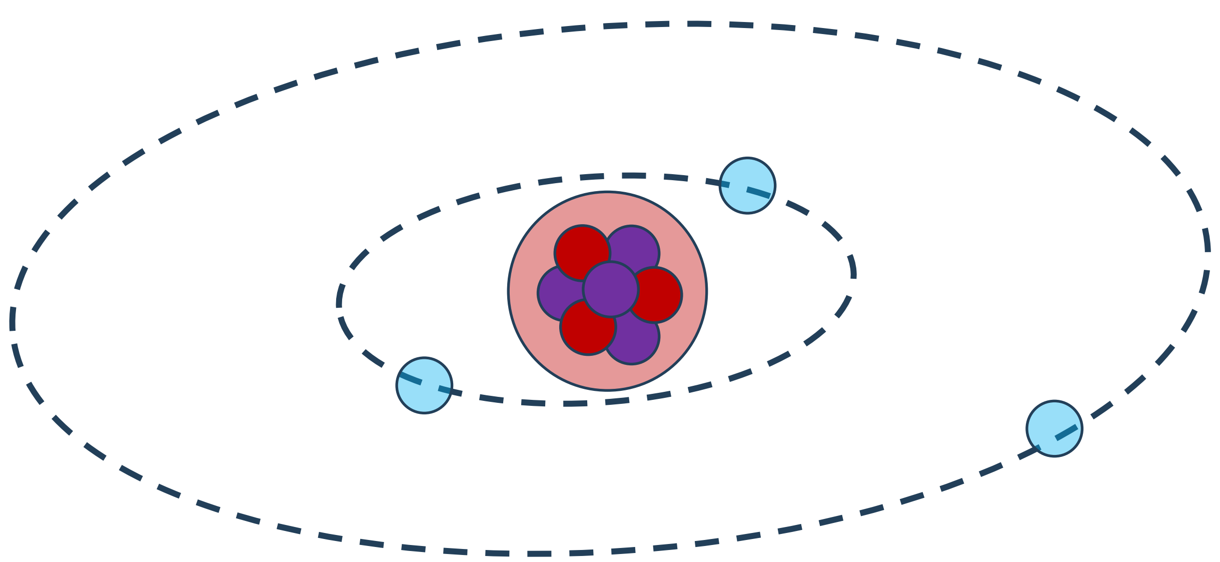
Reihen	Gruppo I. — R^2O	Gruppo II. — RO	Gruppo III. — R^2O^3	Gruppo IV. RH^4 RO^2	Gruppo V. RH^3 R^2O^5	Gruppo VI. RH^2 RO^3	Gruppo VII. RH R^2O^7	Gruppo VIII. — RO^4
1	H=1							
2	Li=7	Be=9,4	B=11	C=12	N=14	O=16	F=19	
3	Na=23	Mg=24	Al=27,3	Si=28	P=31	S=32	Cl=35,5	
4	K=39	Ca=40	—=44	Ti=48	V=51	Cr=52	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	—	— — — —

Periodische Gesetzmässigkeit der Elemente nach Mendeleieff

Reihen	Gruppe I R^2O	Gruppe II RO	Gruppe III R^2O^3	Gruppe IV RH^4 RO^2	Gruppe V RH^3 R^2O^5	Gruppe VI RH^2 RO^3	Gruppe VII RH R^2O^7	Gruppe 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	Sc=44	Ti=48	V=51	Cr=52	Mn=55	Fe=56, Co=59 Ni=59, Cu=63
5	(Cu=63)	Zn=65	Ga=68	–=72	As=75	Se=79	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	Ce=137	La=139	–	Di=145?	–	– – – –
9	(–)	–	–	–	–	–	–	
10	– 165	– 169	Er=170	–173	Ta=182	W=184	–	Pt=194, Os=195? Ir=193, Au=196
11	(Au=196)	Hg=200	Tl=204	Pb=208	Bi=210	–	–	
12	–	–	–	Th=231	–	U=240	–	– – – –

MULTI-ELECTRON ATOMS

- Atoms with higher atom numbers have more electrons and protons
- Number of protons gives the atom number Z
- The weight of the atom can be larger as protons are "separated" by neutrons



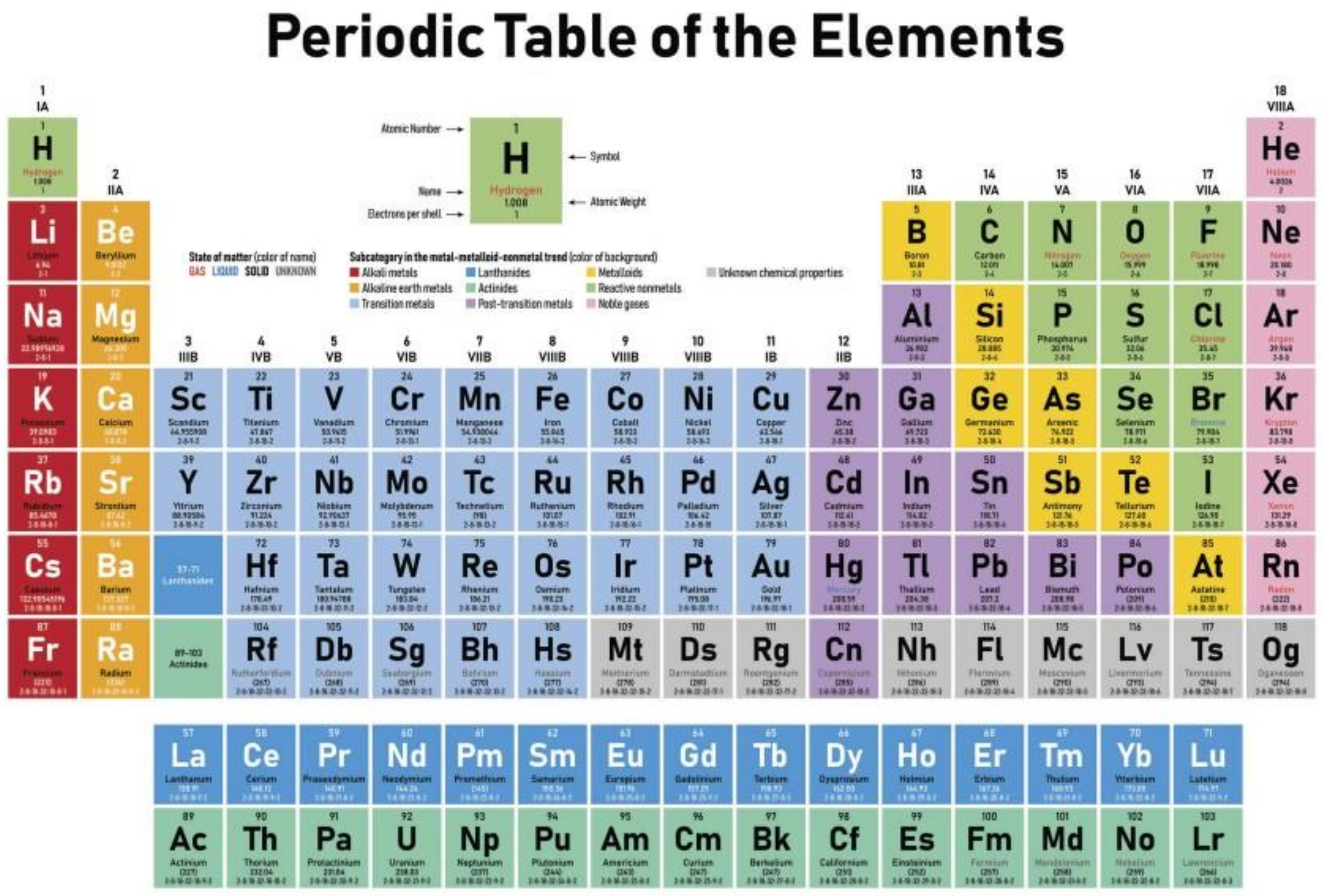
● Nucleus

● Proton (+)

● Neutron

● Electron (-)

- The multiple electrons fill up possible orbitals
- **1869:** Periodic table of Mendeljeev
  - Elements ordered in 8 groups



Periodic Table of the Elements

1 IA	2 IIA	3 IIIB	4 IVB	5 VB	6 VIB	7 VIIB	8 VIIIB	9 VIIIB	10 VIIIB	11 IB	12 IIB	13 IIIA	14 IVA	15 VA	16 VIA	17 VIIA	18 VIIIA
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	57-71 Lanthanides	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra	89-103 Actinides	Rf	Db	Sg	Bh	Hs	Mt	Ds	Rg	Cn	Nh	Fl	Mc	Lv	Ts	Og

La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr

1925: PAULI EXCLUSION PRINCIPLE

No two electrons (fermions) can be in the same quantum state

Electrons in a single atom cannot have all same quantum numbers: n, l, m_l, m_s

- For shell n we have:
  - $n \cdot (2n-1)$ orbitals
  - Maximum $n \cdot (2n-1) \cdot 2$ electrons, each orbital can have one spin-up and one spin-down electron

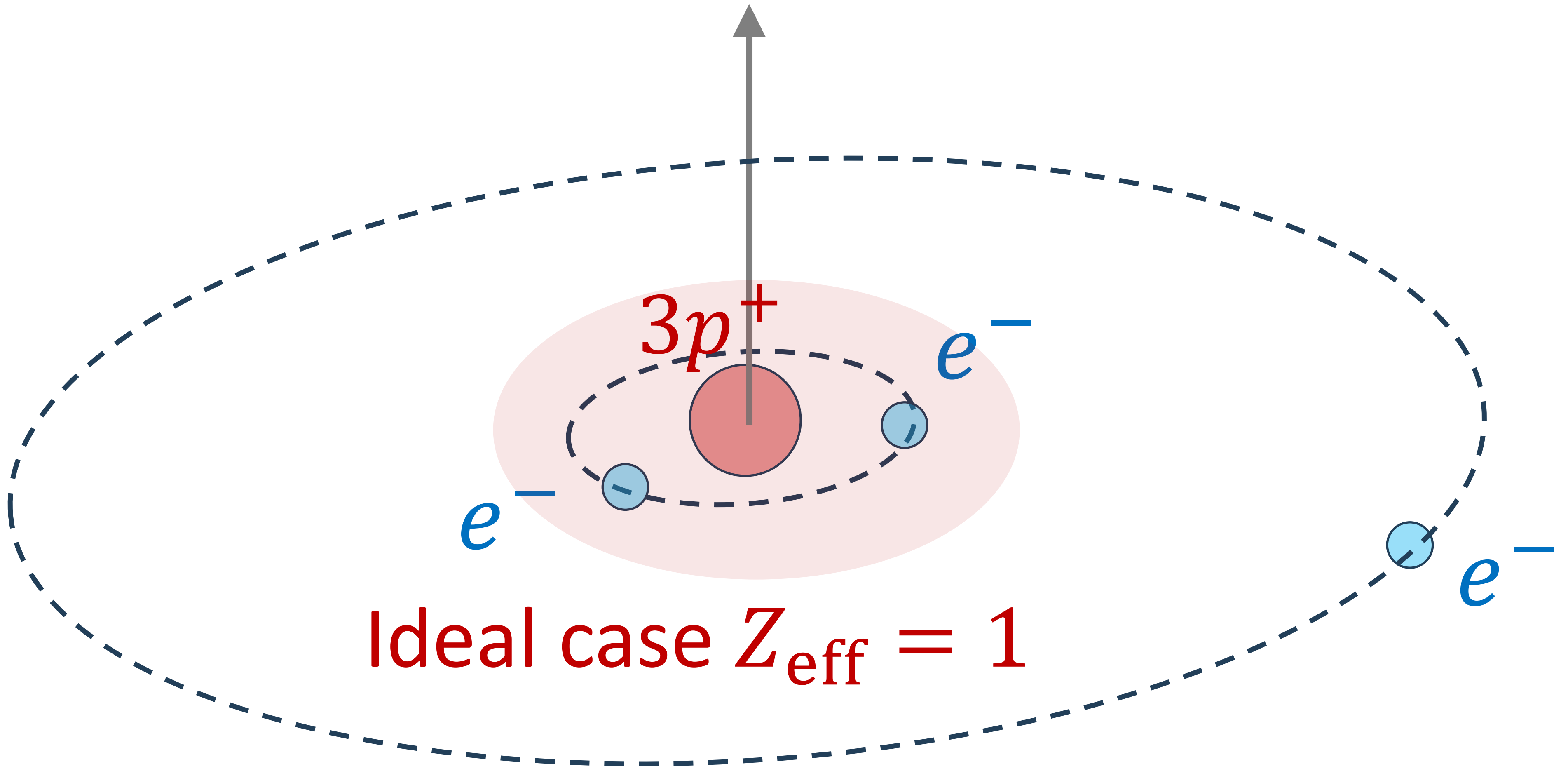
Wolfgang Ernst Pauli

Taken from Wikipedia

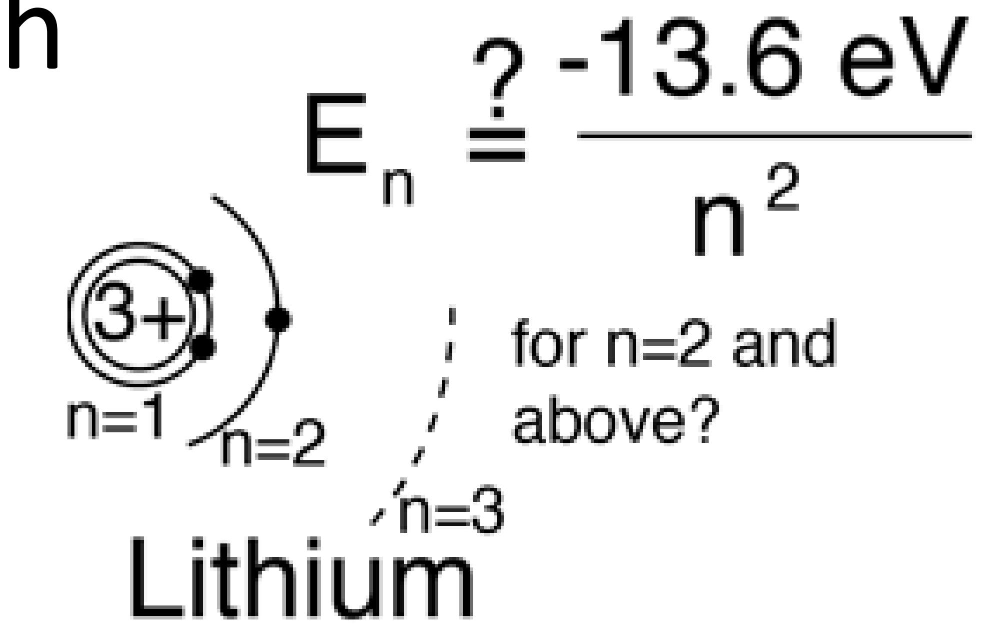
SPECTRA OF MULTI-ELECTRON ATOMS

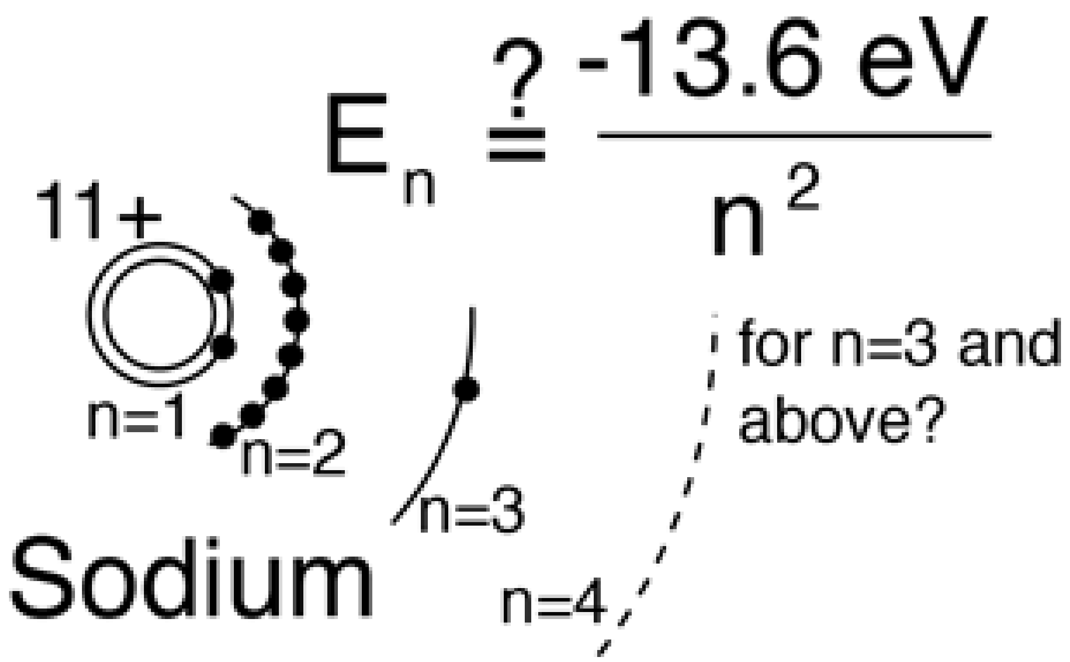
- Energy levels for the electrons?
- Each electron is attracted to the positive nucleus (charge $+eZ$)

$$E_n = -\frac{Z^2}{n^2} \times 13.6\ \text{eV}$$



- But the electrons also interact with each other (repulsion)





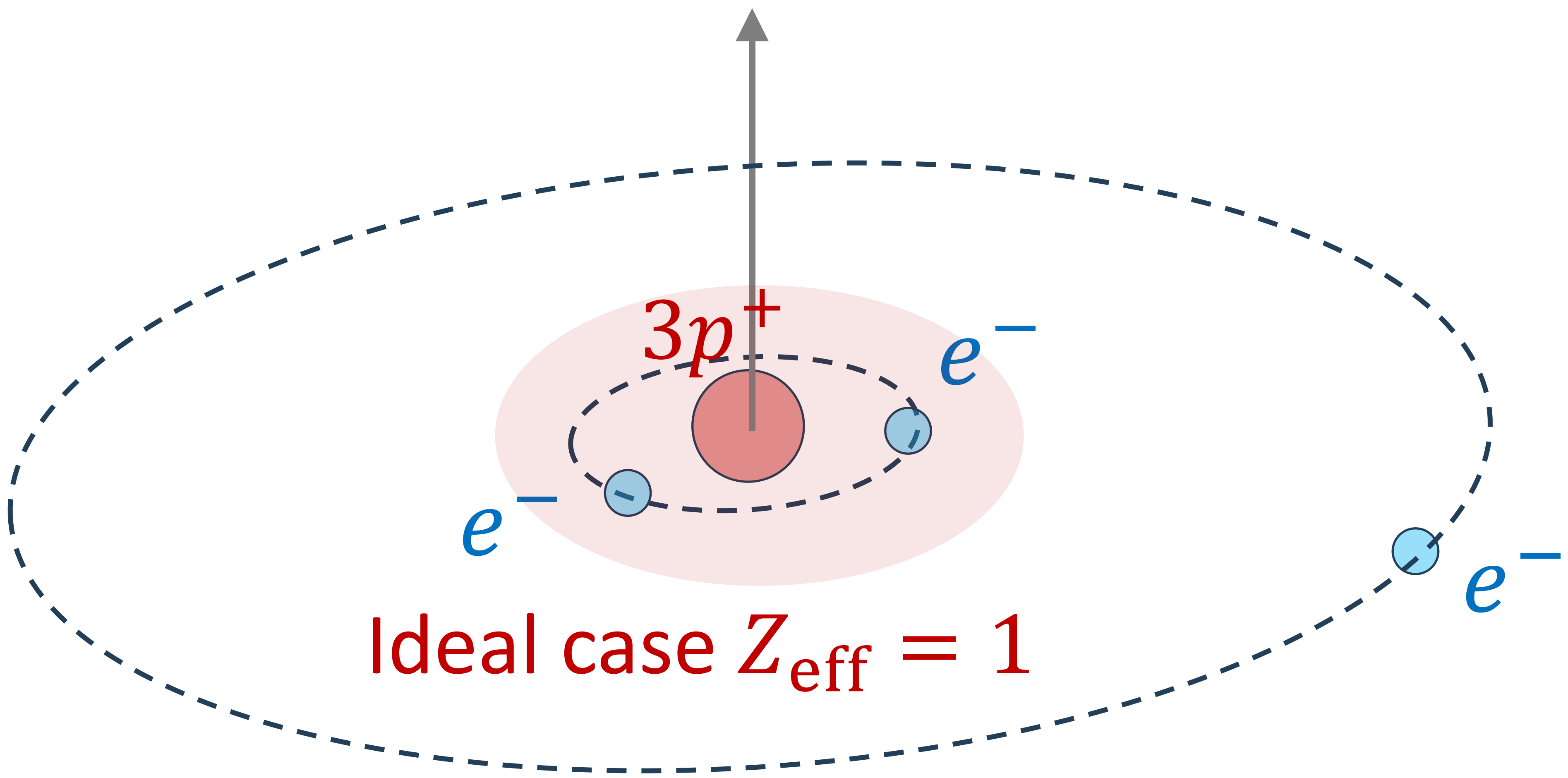
Adapted from: www.hyperphysics.phy-astr.gsu.edu

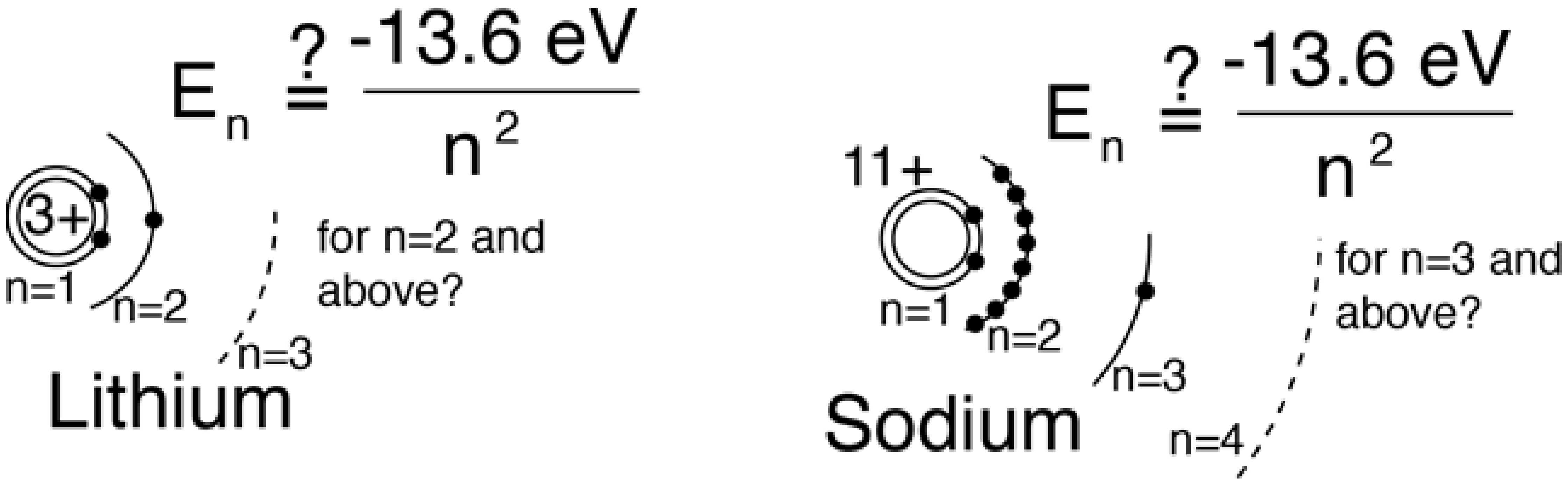
CENTRAL-FIELD APPROXIMATION

- Problem: Electrons interact with each other?
- Inner shells are closer to the nucleus
- If only 1 valence electron: interaction minimal
- Inner electrons shield nucleus partially (max. $Z-1$)

$$Z > Z_{\text{eff}} > 1$$

$$E_n = -\frac{Z_{\text{eff}}^2}{n^2} \times 13.6\text{ eV}$$





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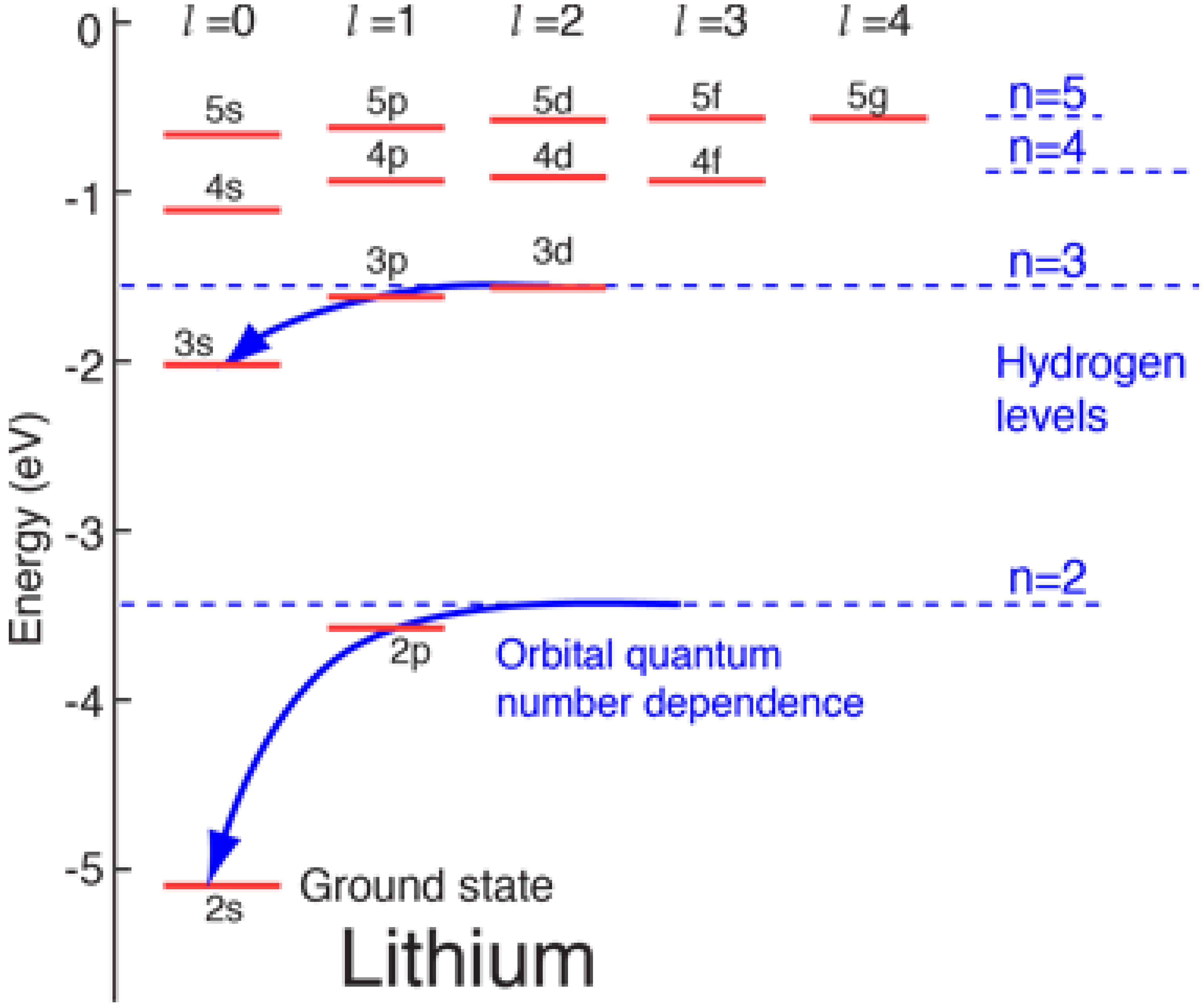
SPECTRA OF MULTI-ELECTRON ATOMS

$$Z > Z_{\text{eff}} > 1$$

- Screening is more effective if farther away: $Z_{\text{eff}} \to 1$
- Lower states have higher Z_{eff}
- Z_{eff} can strongly depend on orbital quantum number l
- s and p states can have different energy

$$E_n = -\frac{Z_{\text{eff}}^2}{n^2} \times 13.6\ \text{eV}$$



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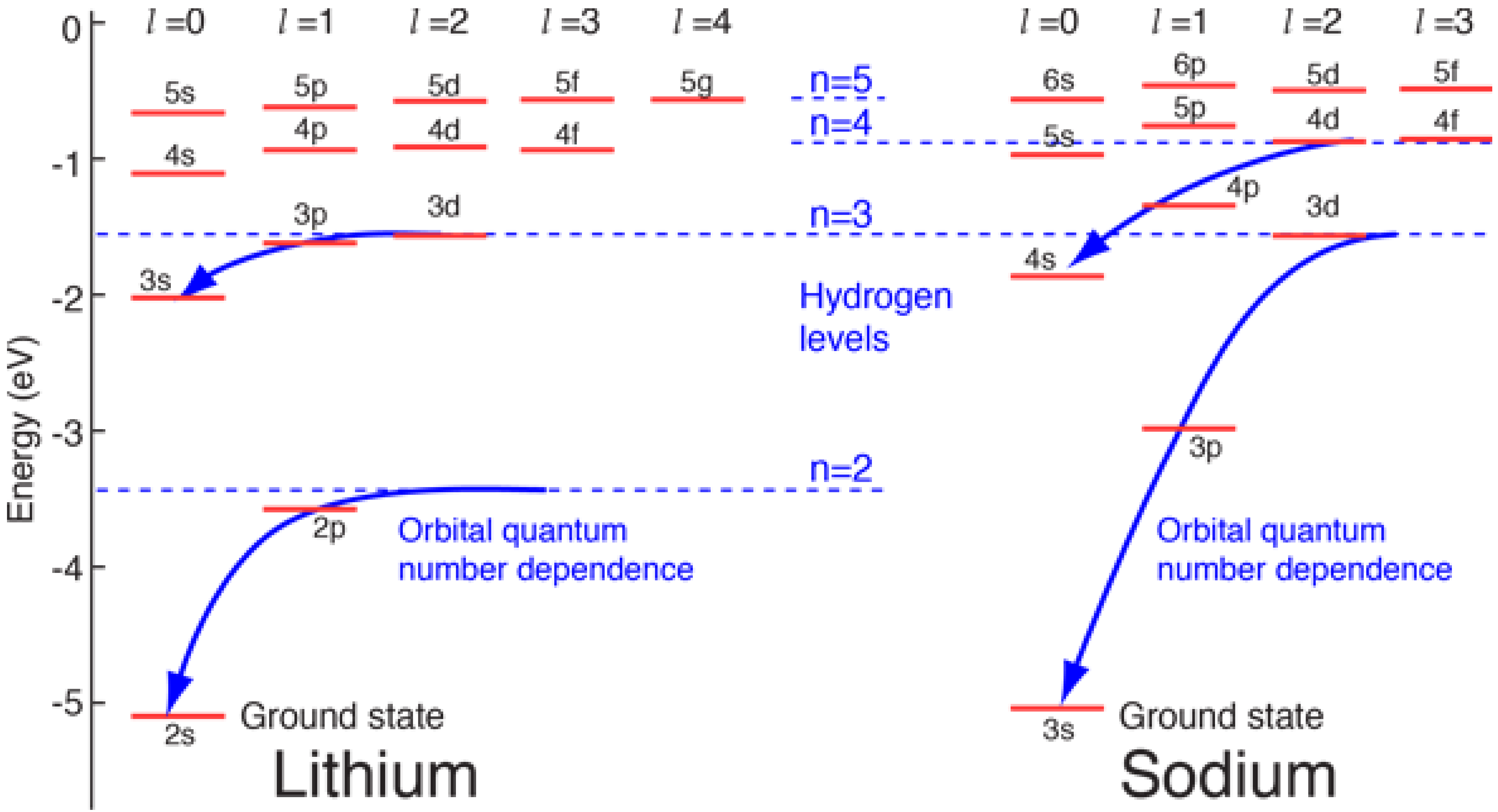

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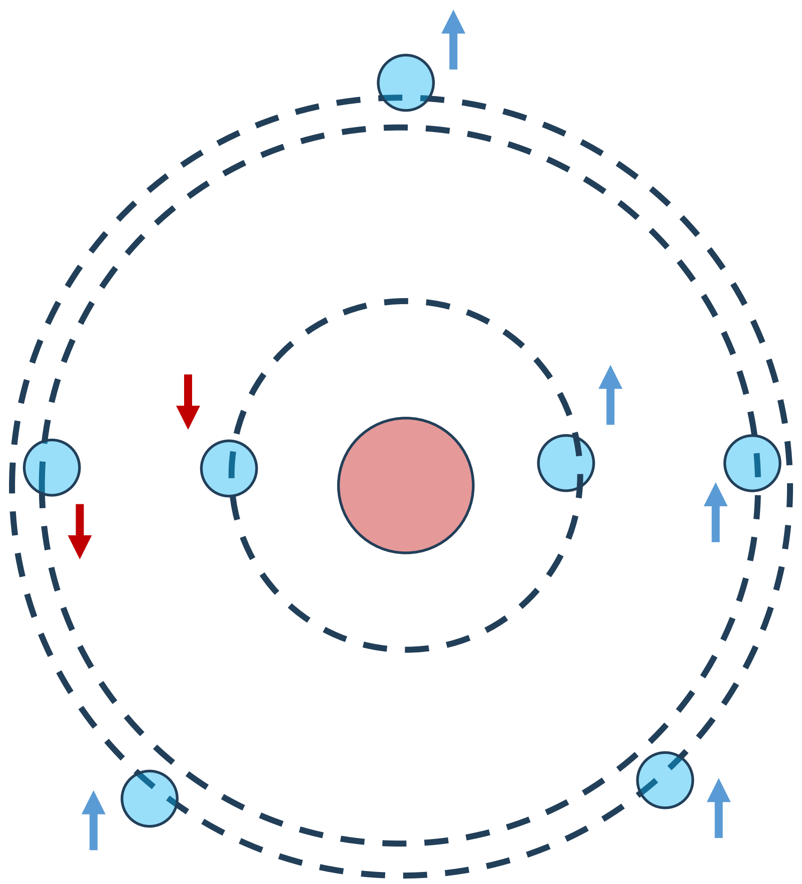
NOTATION FOR ELECTRON CONFIGURATIONS

- Orbital notation (without m_l)
- Use superscript to indicate the number of electrons in the orbital
- Example:

Nitrogen: $1s^2 2s^2 2p^3$

- **1925:** Hund proposes Hund's rules

Electrons prefer to occupy empty orbitals in the same shell first with parallel (up or down spin)



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Friedrich Hund
Taken from Wikipedia

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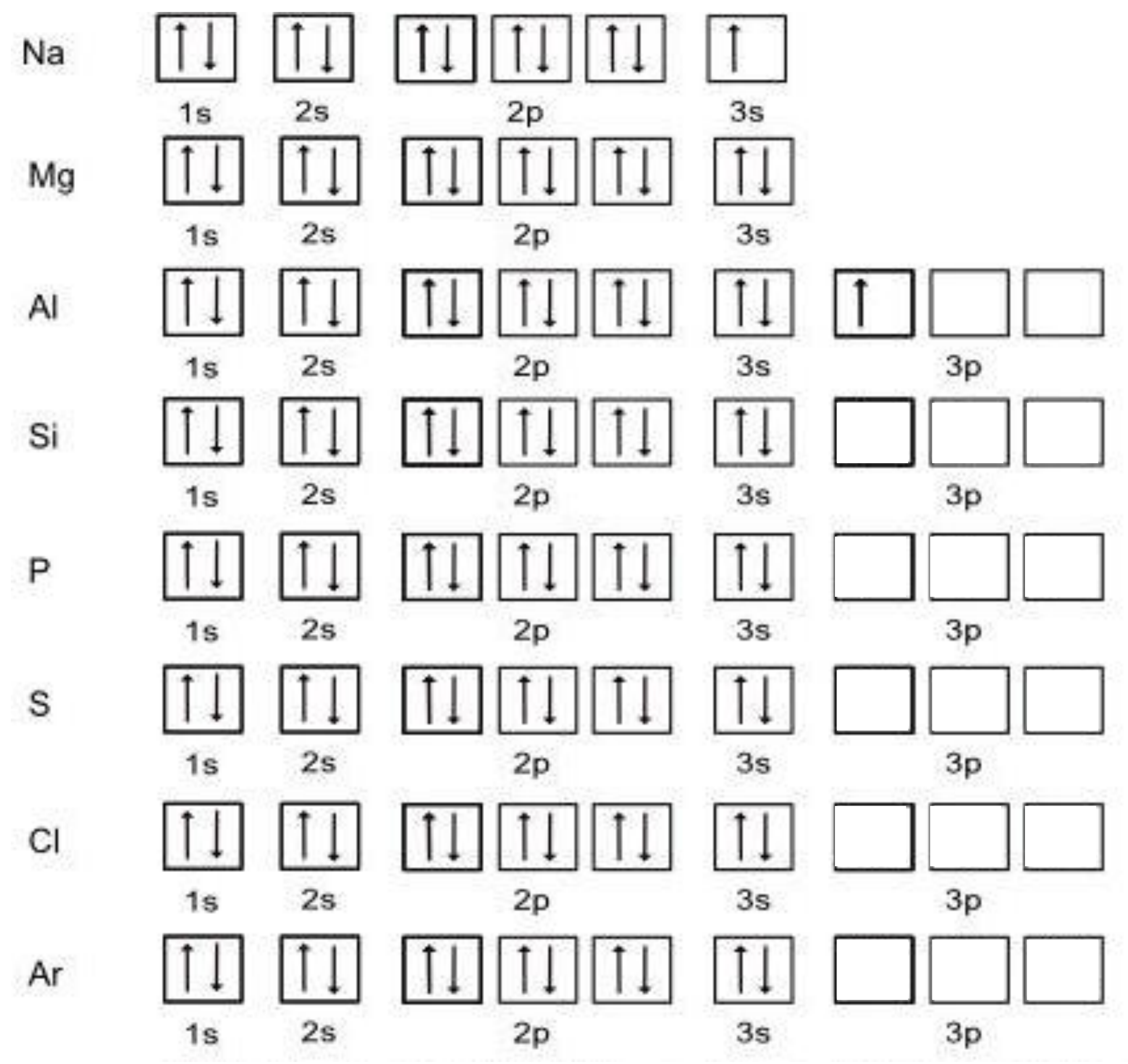

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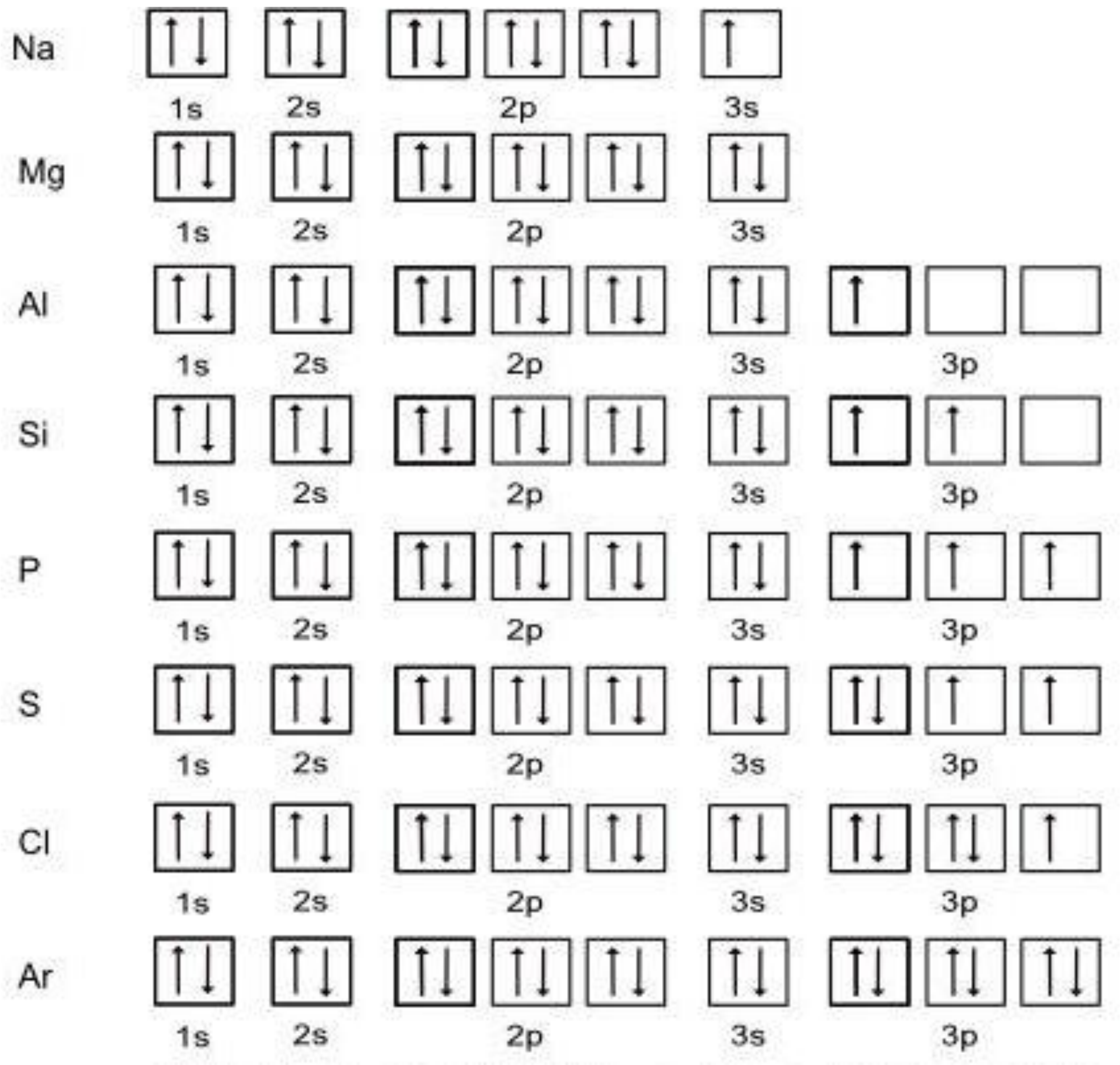

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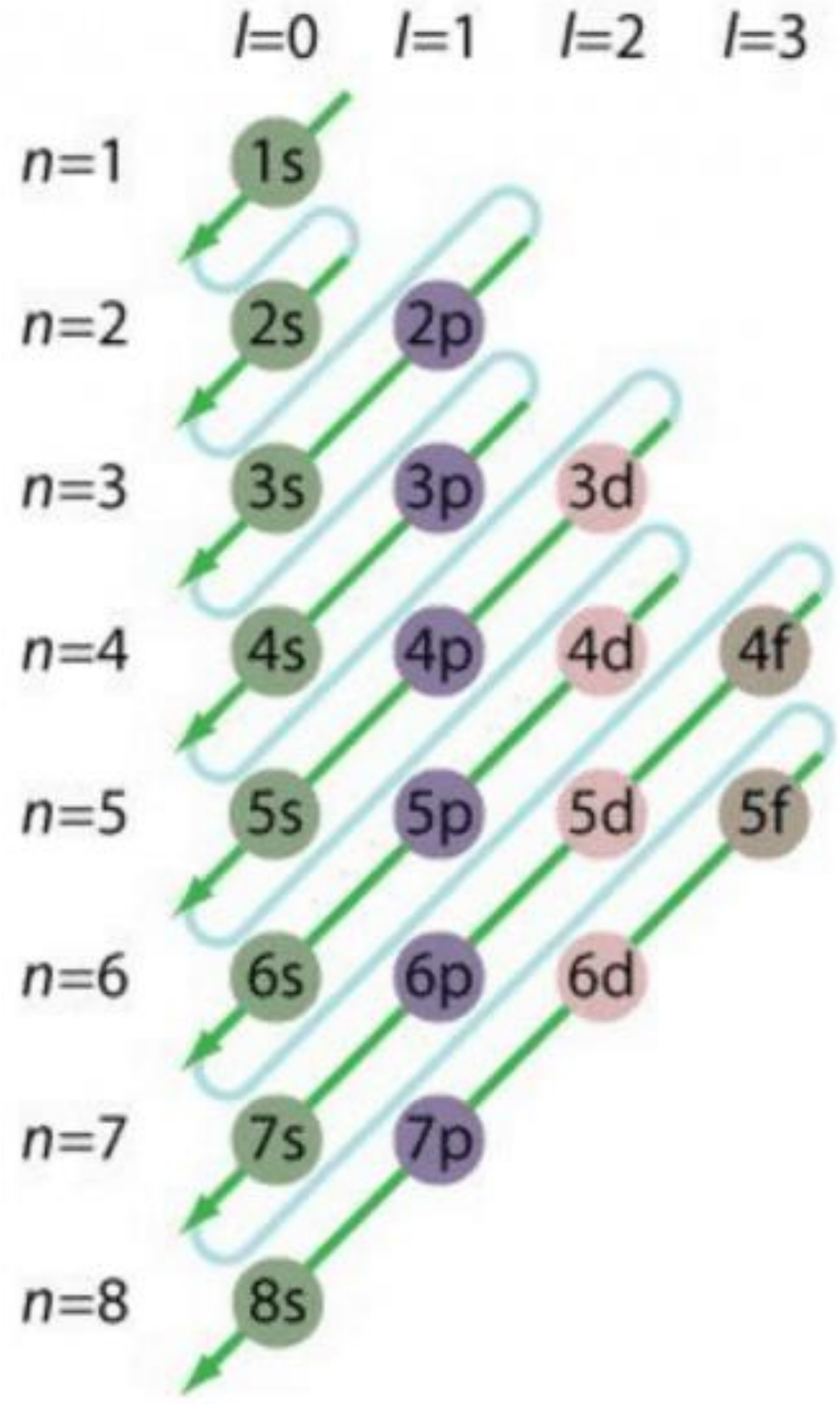
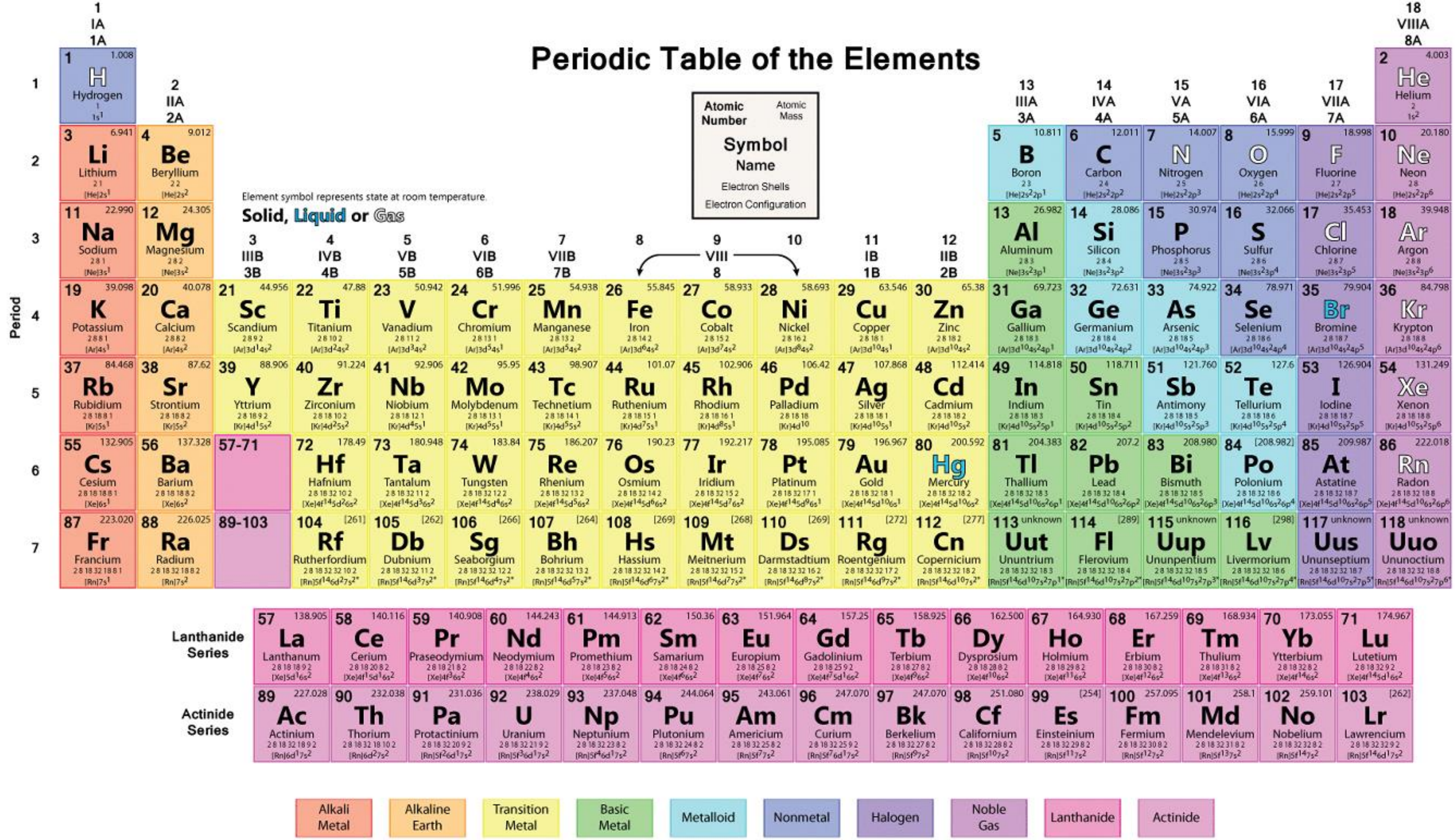


Adapted from: sciencenotes.org/list-of-electron-configurations-of-elements/

Periodic Table of the Elements



Atomic Number
Atomic Mass
Symbol
Name
Electron Shells
Electron Configuration

Element symbol represents state at room temperature.

Solid, Liquid or Gas

Period	1 IA 1A	2 IIA 2A	3 IIIB 3B	4 IVB 4B	5 VB 5B	6 VIB 6B	7 VIIB 7B	8	9 VIII 8	10	11 IB 1B	12 IIB 2B	13 IIIA 3A	14 IVA 4A	15 VA 5A	16 VIA 6A	17 VIIA 7A	18 VIIIA 8A
1	1 1.008 H Hydrogen 1 $1s^1$																	2 4.003 He Helium 2 $1s^2$
2	3 6.941 Li Lithium 2 1 $[He]2s^1$	4 9.012 Be Beryllium 2 2 $[He]2s^2$											5 10.811 B Boron 2 3 $[He]2s^2 2p^1$	6 12.011 C Carbon 2 4 $[He]2s^2 2p^2$	7 14.007 N Nitrogen 2 5 $[He]2s^2 2p^3$	8 15.999 O Oxygen 2 6 $[He]2s^2 2p^4$	9 18.998 F Fluorine 2 7 $[He]2s^2 2p^5$	10 20.180 Ne Neon 2 8 $[He]2s^2 2p^6$
3	11 22.990 Na Sodium 2 8 1 $[Ne]3s^1$	12 24.305 Mg Magnesium 2 8 2 $[Ne]3s^2$											13 26.982 Al Aluminum 2 8 3 $[Ne]3s^2 3p^1$	14 28.086 Si Silicon 2 8 4 $[Ne]3s^2 3p^2$	15 30.974 P Phosphorus 2 8 5 $[Ne]3s^2 3p^3$	16 32.066 S Sulfur 2 8 6 $[Ne]3s^2 3p^4$	17 35.453 Cl Chlorine 2 8 7 $[Ne]3s^2 3p^5$	18 39.948 Ar Argon 2 8 8 $[Ne]3s^2 3p^6$
4	19 39.098 K Potassium 2 8 8 1 $[Ar]4s^1$	20 40.078 Ca Calcium 2 8 8 2 $[Ar]4s^2$	21 44.956 Sc Scandium 2 8 9 2 $[Ar]3d^1 4s^2$	22 47.88 Ti Titanium 2 8 10 2 $[Ar]3d^2 4s^2$	23 50.942 V Vanadium 2 8 11 2 $[Ar]3d^3 4s^2$	24 51.996 Cr Chromium 2 8 13 1 $[Ar]3d^5 4s^1$	25 54.938 Mn Manganese 2 8 13 2 $[Ar]3d^5 4s^2$	26 55.845 Fe Iron 2 8 14 2 $[Ar]3d^6 4s^2$	27 58.933 Co Cobalt 2 8 15 2 $[Ar]3d^7 4s^2$	28 58.693 Ni Nickel 2 8 16 2 $[Ar]3d^8 4s^2$	29 63.546 Cu Copper 2 8 18 1 $[Ar]3d^{10} 4s^1$	30 65.38 Zn Zinc 2 8 18 2 $[Ar]3d^{10} 4s^2$	31 69.723 Ga Gallium 2 8 18 3 $[Ar]3d^{10} 4s^2 4p^1$	32 72.631 Ge Germanium 2 8 18 4 $[Ar]3d^{10} 4s^2 4p^2$	33 74.922 As Arsenic 2 8 18 5 $[Ar]3d^{10} 4s^2 4p^3$	34 78.971 Se Selenium 2 8 18 6 $[Ar]3d^{10} 4s^2 4p^4$	35 79.904 Br Bromine 2 8 18 7 $[Ar]3d^{10} 4s^2 4p^5$	36 84.798 Kr Krypton 2 8 18 8 $[Ar]3d^{10} 4s^2 4p^6$
5	37 84.468 Rb Rubidium 2 8 18 8 1 $[Kr]5s^1$	38 87.62 Sr Strontium 2 8 18 8 2 $[Kr]5s^2$	39 88.906 Y Yttrium 2 8 18 9 2 $[Kr]4d^1 5s^2$	40 91.224 Zr Zirconium 2 8 18 10 2 $[Kr]4d^2 5s^2$	41 92.906 Nb Niobium 2 8 18 12 1 $[Kr]4d^4 5s^1$	42 95.95 Mo Molybdenum 2 8 18 13 1 $[Kr]4d^5 5s^1$	43 98.907 Tc Technetium 2 8 18 14 1 $[Kr]4d^5 5s^2$	44 101.07 Ru Ruthenium 2 8 18 15 1 $[Kr]4d^7 5s^1$	45 102.906 Rh Rhodium 2 8 18 16 1 $[Kr]4d^8 5s^1$	46 106.42 Pd Palladium 2 8 18 18 $[Kr]4d^{10}$	47 107.868 Ag Silver 2 8 18 18 1 $[Kr]4d^{10} 5s^1$	48 112.414 Cd Cadmium 2 8 18 18 2 $[Kr]4d^{10} 5s^2$	49 114.818 In Indium 2 8 18 18 3 $[Kr]4d^{10} 5s^2 5p^1$	50 118.711 Sn Tin 2 8 18 18 4 $[Kr]4d^{10} 5s^2 5p^2$	51 121.760 Sb Antimony 2 8 18 18 5 $[Kr]4d^{10} 5s^2 5p^3$	52 127.6 Te Tellurium 2 8 18 18 6 $[Kr]4d^{10} 5s^2 5p^4$	53 126.904 I Iodine 2 8 18 18 7 $[Kr]4d^{10} 5s^2 5p^5$	54 131.249 Xe Xenon 2 8 18 18 8 $[Kr]4d^{10} 5s^2 5p^6$
6	55 132.905 Cs Cesium 2 8 18 18 8 1 $[Xe]6s^1$	56 137.328 Ba Barium 2 8 18 18 8 2 $[Xe]6s^2$	57-71	72 178.49 Hf Hafnium 2 8 18 32 10 2 $[Xe]4f^{14} 5d^2 6s^2$	73 180.948 Ta Tantalum 2 8 18 32 11 2 $[Xe]4f^{14} 5d^3 6s^2$	74 183.84 W Tungsten 2 8 18 32 12 2 $[Xe]4f^{14} 5d^4 6s^2$	75 186.207 Re Rhenium 2 8 18 32 13 2 $[Xe]4f^{14} 5d^5 6s^2$	76 190.23 Os Osmium 2 8 18 32 14 2 $[Xe]4f^{14} 5d^6 6s^2$	77 192.217 Ir Iridium 2 8 18 32 15 2 $[Xe]4f^{14} 5d^7 6s^2$	78 195.085 Pt Platinum 2 8 18 32 17 1 $[Xe]4f^{14} 5d^9 6s^1$	79 196.967 Au Gold 2 8 18 32 18 1 $[Xe]4f^{14} 5d^{10} 6s^1$	80 200.592 Hg Mercury 2 8 18 32 18 2 $[Xe]4f^{14} 5d^{10} 6s^2$	81 204.383 Tl Thallium 2 8 18 32 18 3 $[Xe]4f^{14} 5d^{10} 6s^2 6p^1$	82 207.2 Pb Lead 2 8 18 32 18 4 $[Xe]4f^{14} 5d^{10} 6s^2 6p^2$	83 208.980 Bi Bismuth 2 8 18 32 18 5 $[Xe]4f^{14} 5d^{10} 6s^2 6p^3$	84 [208.982] Po Polonium 2 8 18 32 18 6 $[Xe]4f^{14} 5d^{10} 6s^2 6p^4$	85 209.987 At Astatine 2 8 18 32 18 7 $[Xe]4f^{14} 5d^{10} 6s^2 6p^5$	86 222.018 Rn Radon 2 8 18 32 18 8 $[Xe]4f^{14} 5d^{10} 6s^2 6p^6$
7	87 223.020 Fr Francium 2 8 18 32 18 8 1 $[Rn]7s^1$	88 226.025 Ra Radium 2 8 18 32 18 8 2 $[Rn]7s^2$	89-103	104 [261] Rf Rutherfordium 2 8 18 32 32 10 2 $[Rn]5f^{14} 6d^2 7s^{2*}$	105 [262] Db Dubnium 2 8 18 32 32 11 2 $[Rn]5f^{14} 6d^3 7s^{2*}$	106 [266] Sg Seaborgium 2 8 18 32 32 12 2 $[Rn]5f^{14} 6d^4 7s^{2*}$	107 [264] Bh Bohrium 2 8 18 32 32 13 2 $[Rn]5f^{14} 6d^5 7s^{2*}$	108 [269] Hs Hassium 2 8 18 32 32 14 2 $[Rn]5f^{14} 6d^6 7s^{2*}$	109 [268] Mt Meitnerium 2 8 18 32 32 15 2 $[Rn]5f^{14} 6d^7 7s^{2*}$	110 [269] Ds Darmstadtium 2 8 18 32 32 16 2 $[Rn]5f^{14} 6d^8 7s^{2*}$	111 [272] Rg Roentgenium 2 8 18 32 32 17 2 $[Rn]5f^{14} 6d^9 7s^{2*}$	112 [277] Cn Copernicium 2 8 18 32 32 18 2 $[Rn]5f^{14} 6d^{10} 7s^{2*}$	113 unknown Uut Ununtrium 2 8 18 32 32 18 3 $[Rn]5f^{14} 6d^{10} 7s^2 7p^{1*}$	114 [289] Fl Flerovium 2 8 18 32 32 18 4 $[Rn]5f^{14} 6d^{10} 7s^2 7p^{2*}$	115 unknown Uup Ununpentium 2 8 18 32 32 18 5 $[Rn]5f^{14} 6d^{10} 7s^2 7p^{3*}$	116 [298] Lv Livermorium 2 8 18 32 32 18 6 $[Rn]5f^{14} 6d^{10} 7s^2 7p^{4*}$	117 unknown Uus Ununseptium 2 8 18 32 32 18 7 $[Rn]5f^{14} 6d^{10} 7s^2 7p^{5*}$	118 unknown Uuo Ununoctium 2 8 18 32 32 18 8 $[Rn]5f^{14} 6d^{10} 7s^2 7p^{6*}$

Lanthanide Series	57 138.905 La Lanthanum 2 8 18 18 9 2 $[Xe]5d^1 6s^2$	58 140.116 Ce Cerium 2 8 18 20 8 2 $[Xe]4f^1 5d^1 6s^2$	59 140.908 Pr Praseodymium 2 8 18 21 8 2 $[Xe]4f^3 6s^2$	60 144.243 Nd Neodymium 2 8 18 22 8 2 $[Xe]4f^4 6s^2$	61 144.913 Pm Promethium 2 8 18 23 8 2 $[Xe]4f^5 6s^2$	62 150.36 Sm Samarium 2 8 18 24 8 2 $[Xe]4f^6 6s^2$	63 151.964 Eu Europium 2 8 18 25 8 2 $[Xe]4f^7 6s^2$	64 157.25 Gd Gadolinium 2 8 18 25 9 2 $[Xe]4f^7 5d^1 6s^2$	65 158.925 Tb Terbium 2 8 18 27 8 2 $[Xe]4f^9 6s^2$	66 162.500 Dy Dysprosium 2 8 18 28 8 2 $[Xe]4f^{10} 6s^2$	67 164.930 Ho Holmium 2 8 18 29 8 2 $[Xe]4f^{11} 6s^2$	68 167.259 Er Erbium 2 8 18 30 8 2 $[Xe]4f^{12} 6s^2$	69 168.934 Tm Thulium 2 8 18 31 8 2 $[Xe]4f^{13} 6s^2$	70 173.055 Yb Ytterbium 2 8 18 32 8 2 $[Xe]4f^{14} 6s^2$	71 174.967 Lu Lutetium 2 8 18 32 9 2 $[Xe]4f^{14} 5d^1 6s^2$
Actinide Series	89 227.028 Ac Actinium 2 8 18 32 18 9 2 $[Rn]6d^1 7s^2$	90 232.038 Th Thorium 2 8 18 32 18 10 2 $[Rn]6d^2 7s^2$	91 231.036 Pa Protactinium 2 8 18 32 20 9 2 $[Rn]5f^2 6d^1 7s^2$	92 238.029 U Uranium 2 8 18 32 21 9 2 $[Rn]5f^3 6d^1 7s^2$	93 237.048 Np Neptunium 2 8 18 32 23 8 2 $[Rn]5f^4 6d^1 7s^2$	94 244.064 Pu Plutonium 2 8 18 32 24 8 2 $[Rn]5f^6 7s^2$	95 243.061 Am Americium 2 8 18 32 25 8 2 $[Rn]5f^7 7s^2$	96 247.070 Cm Curium 2 8 18 32 25 9 2 $[Rn]5f^7 6d^1 7s^2$	97 247.070 Bk Berkelium 2 8 18 32 27 8 2 $[Rn]5f^9 7s^2$	98 251.080 Cf Californium 2 8 18 32 28 8 2 $[Rn]5f^{10} 7s^2$	99 [254] Es Einsteinium 2 8 18 32 29 8 2 $[Rn]5f^{11} 7s^2$	100 257.095 Fm Fermium 2 8 18 32 30 8 2 $[Rn]5f^{12} 7s^2$	101 258.1 Md Mendelevium 2 8 18 32 31 8 2 $[Rn]5f^{13} 7s^2$	102 259.101 No Nobelium 2 8 18 32 32 8 2 $[Rn]5f^{14} 7s^2$	103 [262] Lr Lawrencium 2 8 18 32 32 9 2 $[Rn]5f^{14} 6d^1 7s^2$

Alkali Metal
Alkaline Earth
Transition Metal
Basic Metal
Metalloid
Nonmetal
Halogen
Noble Gas
Lanthanide
Actinide

Atomic number	Symbol	Electron configuration
1	H	$1s^1$
2	He	$1s^2$
3	Li	$[\mathrm{He}]2s^1$
4	Be	$[\mathrm{He}]2s^2$
5	B	$[\mathrm{He}]2s^22p^1$
6	C	$[\mathrm{He}]2s^22p^2$
7	N	$[\mathrm{He}]2s^22p^3$
8	O	$[\mathrm{He}]2s^22p^4$
9	F	$[\mathrm{He}]2s^22p^5$
10	Ne	$[\mathrm{He}]2s^22p^6$
11	Na	$[\mathrm{Ne}]3s^1$
12	Mg	$[\mathrm{Ne}]3s^2$
13	Al	$[\mathrm{Ne}]3s^23p^1$
14	Si	$[\mathrm{Ne}]3s^23p^2$
15	P	$[\mathrm{Ne}]3s^23p^3$
16	S	$[\mathrm{Ne}]3s^23p^4$
17	Cl	$[\mathrm{Ne}]3s^23p^5$
18	Ar	$[\mathrm{Ne}]3s^23p^6$
19	K	$[\mathrm{Ar}]4s^1$
20	Ca	$[\mathrm{Ar}]4s^2$
21	Sc	$[\mathrm{Ar}]4s^23d^1$
22	Ti	$[\mathrm{Ar}]4s^23d^2$
37	Rb	$[\mathrm{Kr}]5s^1$
38	Sr	$[\mathrm{Kr}]5s^2$
39	Y	$[\mathrm{Kr}]5s^24d^1$
40	Zr	$[\mathrm{Kr}]5s^24d^2$
41	Nb	$[\mathrm{Kr}]5s^14d^4$
42	Mo	$[\mathrm{Kr}]5s^14d^5$
43	Tc	$[\mathrm{Kr}]5s^24d^5$
44	Ru	$[\mathrm{Kr}]5s^14d^7$
45	Rh	$[\mathrm{Kr}]5s^14d^8$
46	Pd	$[\mathrm{Kr}]4d^{10}$
47	Ag	$[\mathrm{Kr}]5s^14d^{10}$
48	Cd	$[\mathrm{Kr}]5s^24d^{10}$
49	In	$[\mathrm{Kr}]5s^24d^{10}5p^1$
50	Sn	$[\mathrm{Kr}]5s^24d^{10}5p^2$
51	Sb	$[\mathrm{Kr}]5s^24d^{10}5p^3$
52	Te	$[\mathrm{Kr}]5s^24d^{10}5p^4$
53	I	$[\mathrm{Kr}]5s^24d^{10}5p^5$
54	Xe	$[\mathrm{Kr}]5s^24d^{10}5p^6$
55	Cs	$[\mathrm{Xe}]6s^1$
56	Ba	$[\mathrm{Xe}]6s^2$
57	La	$[\mathrm{Xe}]6s^25d^1$
58	Ce	$[\mathrm{Xe}]6s^24f^15d^1$
73	Ta	$[\mathrm{Xe}]6s^24f^{14}5d^3$
74	W	$[\mathrm{Xe}]6s^24f^{14}5d^4$
75	Re	$[\mathrm{Xe}]6s^24f^{14}5d^5$
76	Os	$[\mathrm{Xe}]6s^24f^{14}5d^6$
77	Ir	$[\mathrm{Xe}]6s^24f^{14}5d^7$
78	Pt	$[\mathrm{Xe}]6s^14f^{14}5d^9$
79	Au	$[\mathrm{Xe}]6s^14f^{14}5d^{10}$
80	Hg	$[\mathrm{Xe}]6s^24f^{14}5d^{10}$
81	Tl	$[\mathrm{Xe}]6s^24f^{14}5d^{10}6p^1$
82	Pb	$[\mathrm{Xe}]6s^24f^{14}5d^{10}6p^2$
83	Bi	$[\mathrm{Xe}]6s^24f^{14}5d^{10}6p^3$
84	Po	$[\mathrm{Xe}]6s^24f^{14}5d^{10}6p^4$
85	At	$[\mathrm{Xe}]6s^24f^{14}5d^{10}6p^5$
86	Rn	$[\mathrm{Xe}]6s^24f^{14}5d^{10}6p^6$
87	Fr	$[\mathrm{Rn}]7s^1$
88	Ra	$[\mathrm{Rn}]7s^2$
89	Ac	$[\mathrm{Rn}]7s^26d^1$
90	Th	$[\mathrm{Rn}]7s^26d^2$
91	Pa	$[\mathrm{Rn}]7s^25f^26d^1$
92	U	$[\mathrm{Rn}]7s^25f^36d^1$
93	Np	$[\mathrm{Rn}]7s^25f^46d^1$
94	Pu	$[\mathrm{Rn}]7s^25f^6$