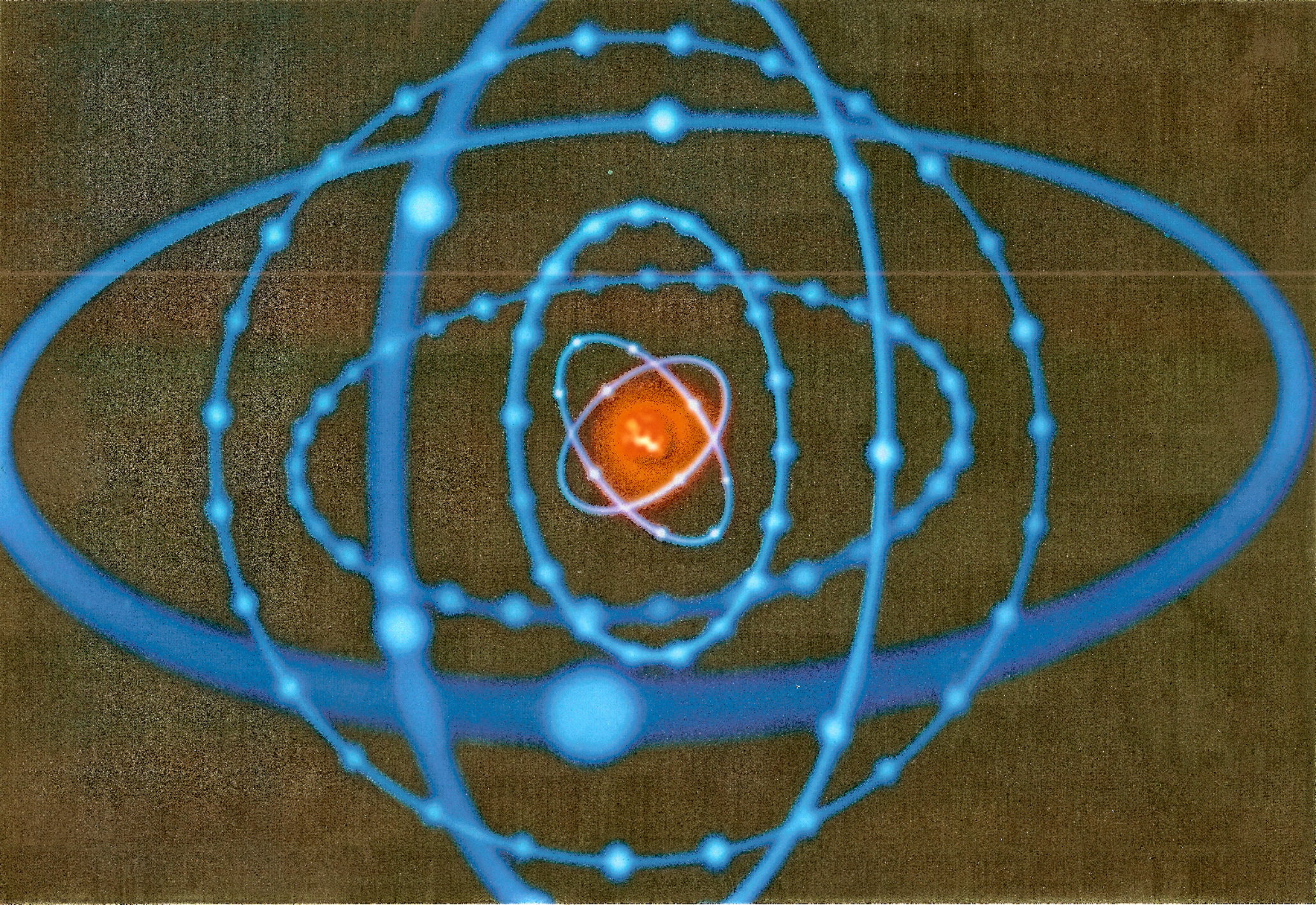
Advanced Courses Offered by the Atomic Physics Division.

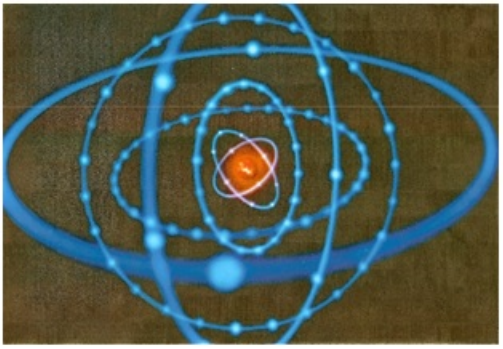
All are open for Science faculty students and given in English

Fall 1	Fall 2	Spring 1	Spring 2
> Engineering			
Optics and Optical Design FAFF01, FYST43, 7.5 hp	Lasers FAFN01, FYSN14, 7.5 hp	Optoelectronics Optoelectronics FFFN15 / FYST48 7.5 hp	Advanced Optics and Lasers FAFN10, FYST32 7.5 hp
Atomic & molecular spectroscopy FAF080, FYST14, 7.5 hp	Medical Optics Will be given in 2019 for the first time, 7.5 hp	Laser-based combustion diagnostics FBR024, FYST28, 7.5 hp Light-Matter Interaction FAFN05, FYST21, 7.5 hp	Quantum Information (odd years) FAFN40, FYST30 7.5 hp Quantum Optics (even years) (no course code yet) 7.5 hp

Uses the second half of the book by Foot

You may take individual courses or any combination up to a Masters program in Photonics. This education program is coupled to world-leading research activities in optics, lasers and their applications, performed at the Lund Laser Centre (LLC). LLC is the largest unit in the Nordic countries within the field of lasers, optics and spectroscopy, and a large scale facility of the European Union, part of Laserlab-Europe. It has recently been selected as one of the 20 best research environments in Sweden, receiving a prestigious Linné grant.





- **One electron atoms, H-like.**

  Bohr model

  Exact quantum mechanical results

- **Hydrogenic-, Rydberg-atoms. Quantum defect**

  Accurate semi-empirical results

- **Many electron atoms.**

  Approximations CFA + LS/jj- coupling

- **Magnetic interactions**

  Spin-orbit, Hyperfine and

  External mag. fields

- **Transitions**

  Selection rules and line widths

- **Molecules**

The Bohr atom.

Results in a quantized one-electron (H-like) system

$$r_n = a_0 \frac{n^2}{Z}, \quad a_0 = 0,53 \text{ Å}.$$

$$v_n = \alpha \cdot c \cdot \frac{Z}{n}, \quad \alpha \approx \frac{1}{137}.$$

$$E_n = -R \cdot \frac{Z^2}{n^2}, \quad R = 109677 \text{cm}^{-1} \text{ for H}$$

$$\frac{1}{\lambda} = E_{n_1} - E_{n_2} = R \cdot Z^2 \left(\frac{1}{n_1^2} - \frac{1}{n_2^2}\right). \quad \text{Rydberg formula}$$

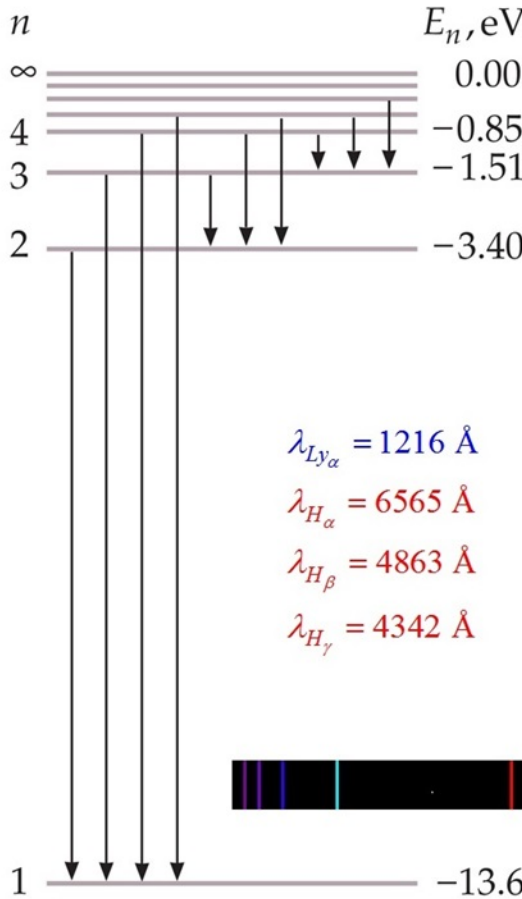
1 eV = 8066 cm^{-1}

Spectral series:
Lyman, Balmer, Paschen, Brackett, Pfund, Humphreyes.....

Mass dependence of the Rydberg constant for an element with nuclear mass M and massnumber A:

$$R_M = \frac{1}{1+\frac{m}{M}} R_\infty = \frac{1}{1+\frac{1}{1836 \cdot A}} R_\infty, \quad R_\infty = 109737 \text{ cm}^{-1}$$

Spectral series in H



Quantum mechanical treatment of one-electron systems

$$H\Psi = E\Psi$$

$$H = -\frac{\hbar^2}{2\mu}\left(\frac{\partial^2}{\partial x^2}+\frac{\partial^2}{\partial y^2}+\frac{\partial^2}{\partial z^2}\right)-\frac{Ze^2}{4\pi\varepsilon_0 r}$$

The Hamilton operator in spherical polar coordinates:

$$\hat{H} = -\frac{\hbar^2}{2\mu}\left[\frac{1}{r}\frac{\partial^2}{\partial r^2}r+\frac{1}{r^2\sin(\theta)}\left(\frac{\partial}{\partial\theta}\sin(\theta)\frac{\partial}{\partial\theta}\right)+\frac{1}{r^2\sin^2(\theta)}\frac{\partial^2}{\partial\phi^2}\right]-\frac{Ze^2}{4\pi\varepsilon_0 r}$$

$\boldsymbol{L}^2$ in spherical polar coordinates

$$\hat{L}^2 = -\hbar^2\left[\frac{1}{\sin(\theta)}\left(\frac{\partial}{\partial\theta}\sin(\theta)\frac{\partial}{\partial\theta}\right)+\frac{1}{\sin^2(\theta)}\frac{\partial^2}{\partial\phi^2}\right]$$

thus

$$\hat{H} = -\frac{\hbar^2}{2\mu}\frac{1}{r}\frac{\partial^2}{\partial r^2}r+\frac{\hat{L}^2}{2\mu r^2}-\frac{Ze^2}{4\pi\varepsilon_0 r}$$

Spherically symmetric

Used again in the central-field approximation

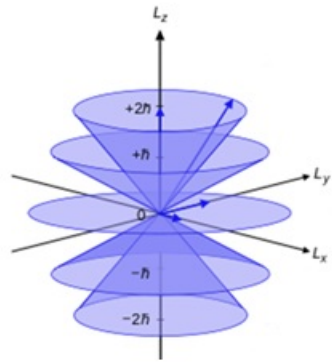
Since $\boldsymbol{L}^2$ only contains angular coordinates $[\boldsymbol{H}, \boldsymbol{L}^2] = 0$, i.e. H and $\boldsymbol{L}^2$ have common eigenfunctions that we may write as:

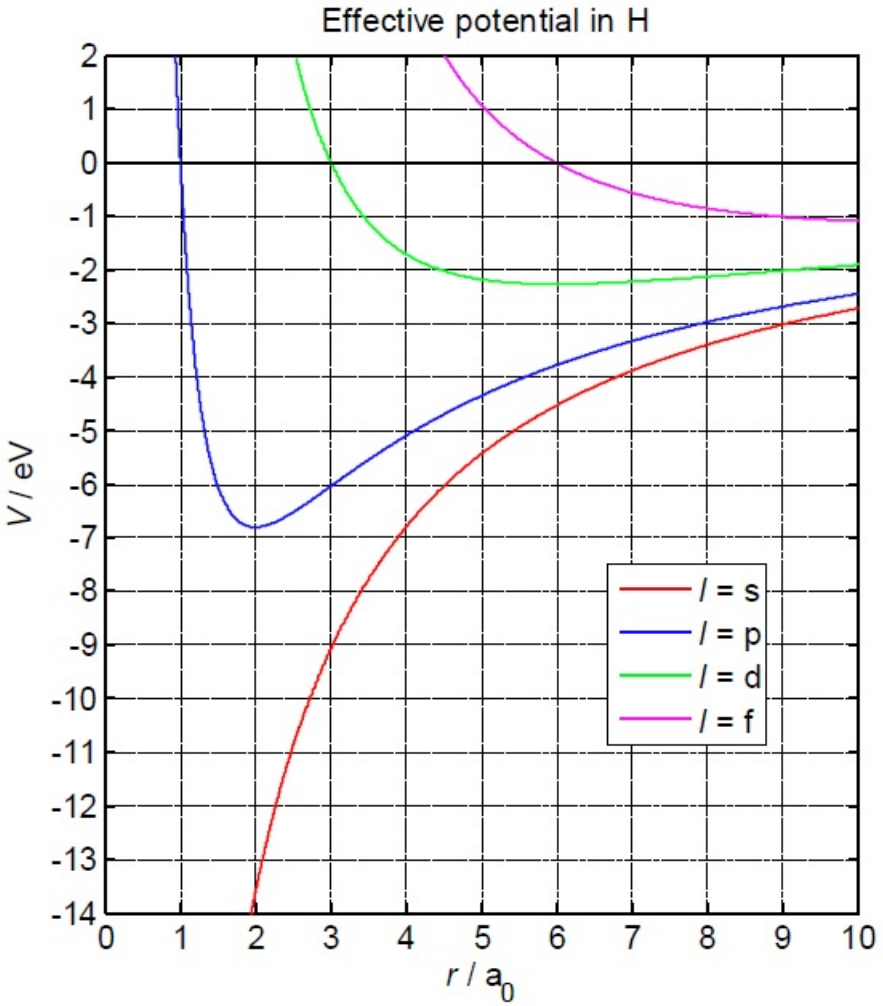
$$\Psi_{n,\ell,m_\ell}(r,\theta,\varphi) = R_{n,\ell}(r)\cdot Y_{\ell,m_\ell}(\theta,\varphi)$$

where

$$L^2 Y_{\ell,m_\ell}(\theta,\varphi) = \hbar^2\ell(\ell+1)\cdot Y_{\ell,m_\ell}(\theta,\varphi)$$
$$L_z Y_{\ell,m_\ell}(\theta,\varphi) = \hbar m_\ell \cdot Y_{\ell,m_\ell}(\theta,\varphi)$$

and ℓ is an integer, $\ell = 0, 1, 2\ldots n\text{-}1$
and $m_\ell = -\ell, -\ell+1, \ldots\ldots \ell\text{-}1, \ell$



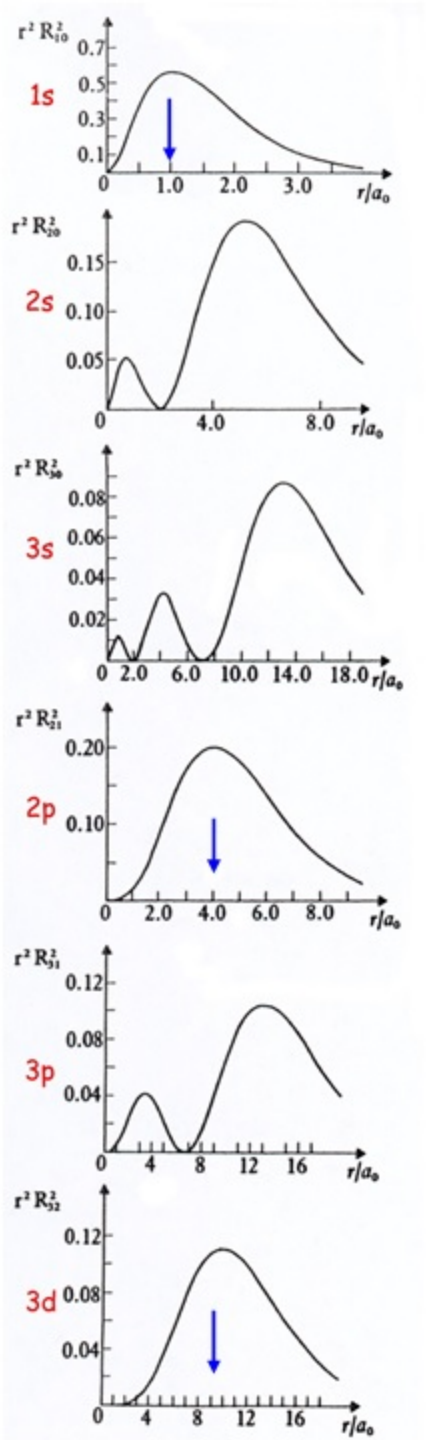


$$V_{\text{eff}} = \frac{\hbar^2 \ell \cdot (\ell + 1)}{2\mu \cdot r^2} - \frac{Ze^2}{4\pi\varepsilon_0 \cdot r}$$

Note, only s-electrons can move close or into the nucleus.

- ⇨ **Large quantum defect for s-electrons**
- ⇨ **Large hyperfine structure for unpaired s-electrons**
- ⇨ **Only s-electrons experience the charge distribution <u>inside</u> the nucleus giving rise to the so-called volume shift.**

Radial probability distribution in H.



For 1s, 2p, 3d,... i.e.

$n, \ell = n - 1$

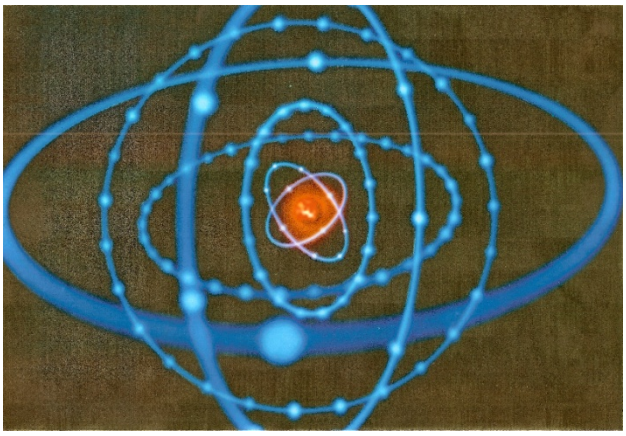
the most probable distance r_n is given by:

$$r_n = a_0 \frac{n^2}{Z}$$

i.e. the same result as in the Bohr model!

Number of minima:

$N = n - \ell - 1$



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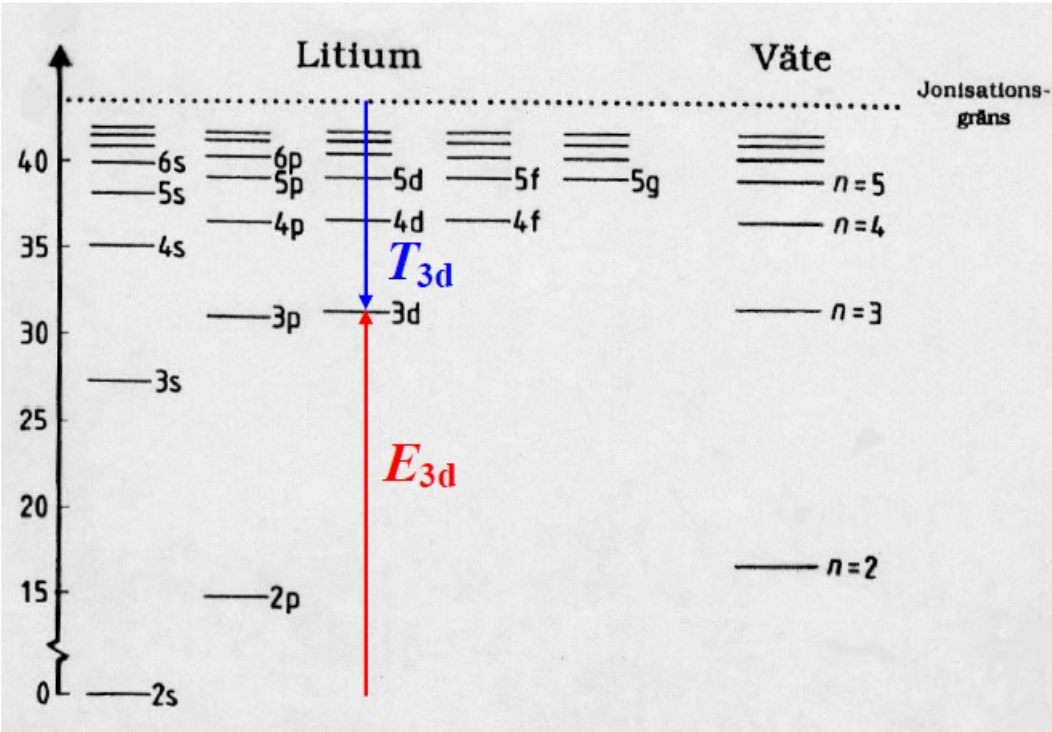
Term values in Li and H.

$$T = E_{jon} - E$$



	T_{exp} / cm^{-1}	$T_H = R_{Li}/9$ / cm^{-1}	% fel
$1s^2 3s$	16281	12192	33
$1s^2 3p$	12562	-"-	3
$1s^2 3d$	12204	-"-	0.1

Quantum defect in F VII

$$T = R \cdot \frac{Z^2}{n^2}$$ H-like

$$T = R \cdot \frac{\zeta^2}{n^2}$$ Completely screened nucleus

$$\zeta = Z - N_{\text{iner}}$$

$$T = R \cdot \frac{\zeta^2}{(n-\delta)^2}$$ δ = quantum defect

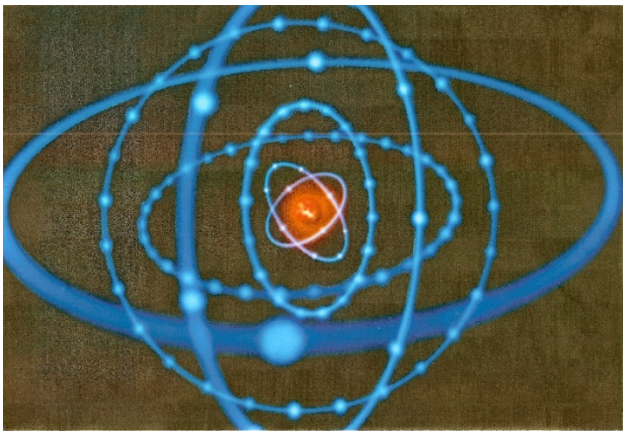
δ is:

- experimentally determined
- strongly dependent of ℓ
- approximately independent of n.

Quantum defect in F VII (Li-like)

n	*s*	*p*	*d*	*f*	*g*
2	0.1026	0.02660			
3	0.0992	0.02693	0.001295		
4	0.0983	0.02711	0.001794	0.000262	
5	0.0979	0.02718	0.002030	0.000466	0.000181
6	0.0976	0.02782	0.002016	0.000529	0.000266
7	0.0975		0.002147	0.000455	-
8			0.002665	0.000528	0.000304
9				0.000530	

Engström, L., Physica Scripta 29, **113** (1984)



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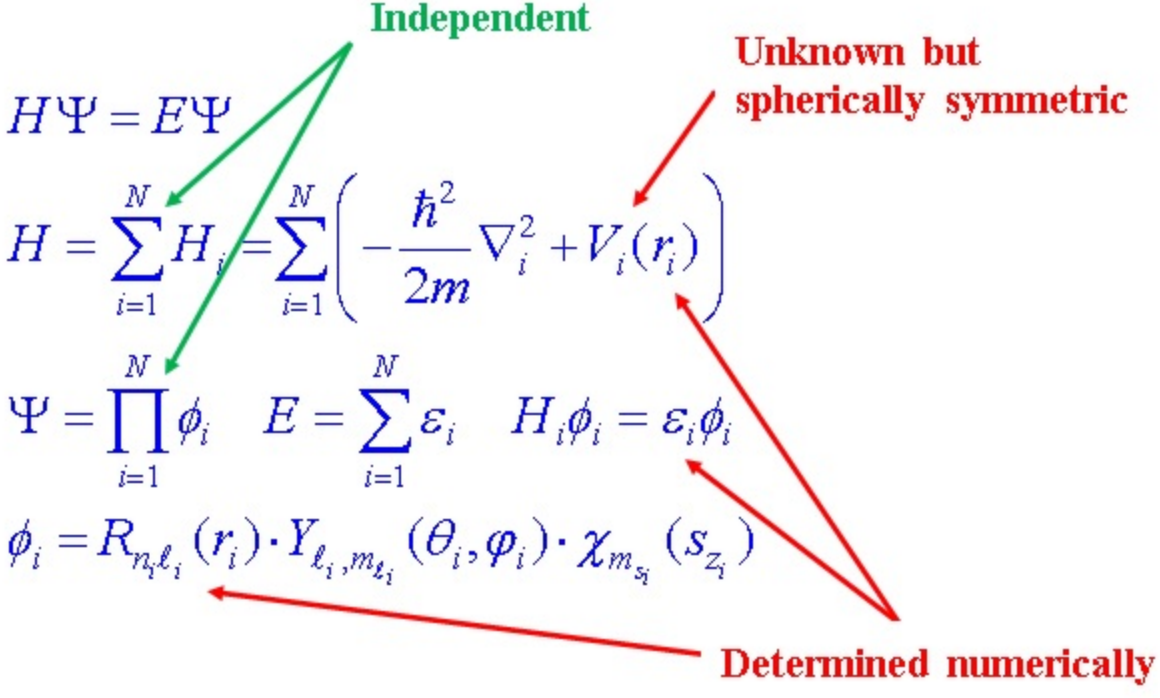
The central field approximation

- **Each electron moves independently of the other in the electrostatic field from the nucleus and the other N - 1 electrons.**

- **This field is assumed to be spherically symmetric.**



Configurations in Ne I

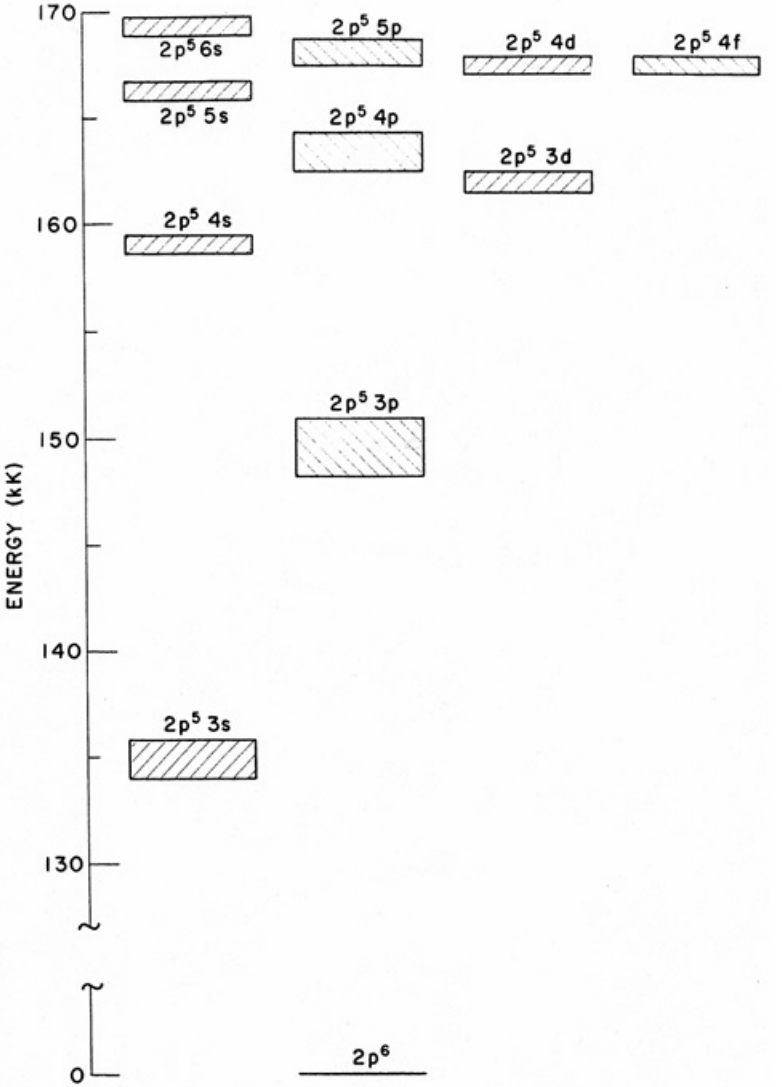


Fig. 4-1. Block diagram of the lowest configurations of Ne I. The levels of each configuration lie within the limited energy range shown by the corresponding shaded block. (There is one level in $2p^6$, and there are four levels in each p^5s configuration, ten levels in each p^5p, and twelve levels in each p^5d or p^5f configuration.)

The physical background to the periodic table of the elements.

1. Number of quantum states N:

   a) Given n and ℓ. Orbital / subshell

   $N = 2 \cdot (2\ell + 1)$ due to m_s and m_ℓ.

   b) Given n. Shell

   $N = 2n^2$

$$N = \sum_{\ell=0}^{n-1} 2(2\ell+1) = \sum_{\ell=0}^{n-1} 4\ell + \sum_{\ell=0}^{n-1} 2 = 4\frac{n(n-1)}{2} + 2n = 2n^2$$

2. Highest binding energy for low n and ℓ due to the quantum defect

3. Pauli principle, i.e. antisymmetric wave-functions, demanding that no 2 electrons have all 4 quantum numbers identical

Periodic System (first four rows)

H 1s																He $1s^2$	Filled K-shell
Li 2s	Be $2s^2$										B 2p	C $2p^2$	N $2p^3$	O $2p^4$	F $2p^5$	Ne $2p^6$	Filled L-shell
Na 3s	Mg $3s^2$										Al 3p	Si $3p^2$	P $3p^3$	S $3p^4$	Cl $3p^5$	Ar $3p^6$	8 outer electrons $3s^2 3p^6$
K 4s	Ca $4s^2$	Sc 3d	Ti $3d^2$	V $3d^3$	Cr $3d^4$	Mn $3d^5$	Fe $3d^6$	Co $3d^7$	Ni $3d^8$	Cu $3d^9$	Zn $3d^{10}$	Ga 4p	Ge $4p^2$	As $4p^3$	Se $4p^4$	Br $4p^5$	Xe $4p^6$	8 outer electrons $4s^2 4p^6$

.....

.....

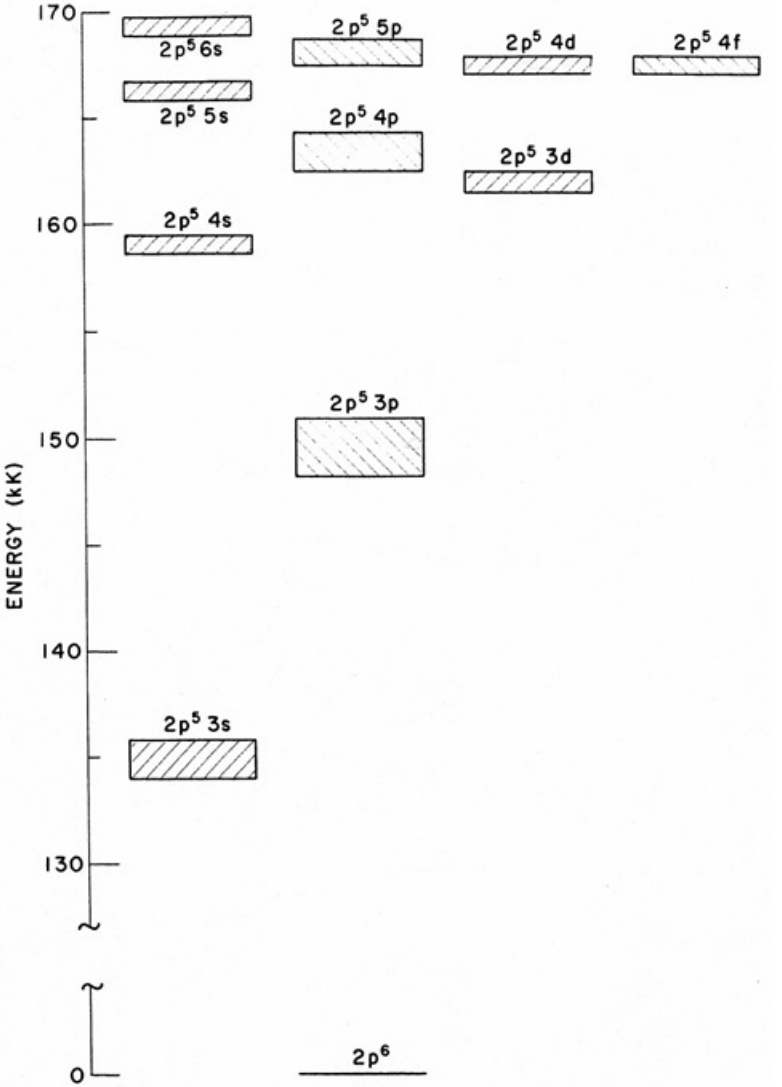
Alkali metals

Alkaline earths

Halogens

Noble gases

Configurations in Ne I



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LS-coupling

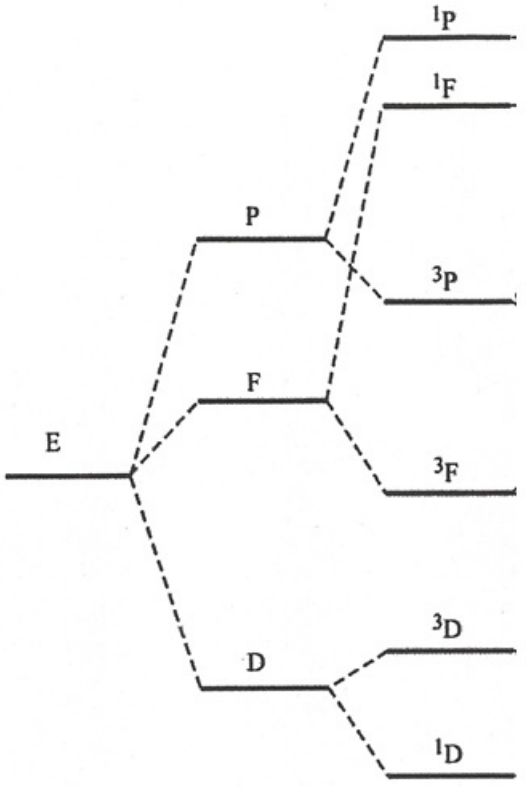
$$\hat{L} = \sum_{i=1}^{N} \hat{\ell}_i, \quad \hat{S} = \sum_{i=1}^{N} \hat{s}_i$$

(Note NOT $\hat{J} = \hat{L} + \hat{S}$!!)

Assume no spin-dependent terms in $\hat{H}$ i.e. no spin-orbit interaction, then $[\hat{H}, \hat{J}] = [\hat{H}, \hat{S}] = [\hat{H}, \hat{L}] = 0$. Thus all energy levels must be characterized by the quantum numbers, L, S and J.

Notation: ${}^{2S+1}L_J$

pd-configuration LS-coupling

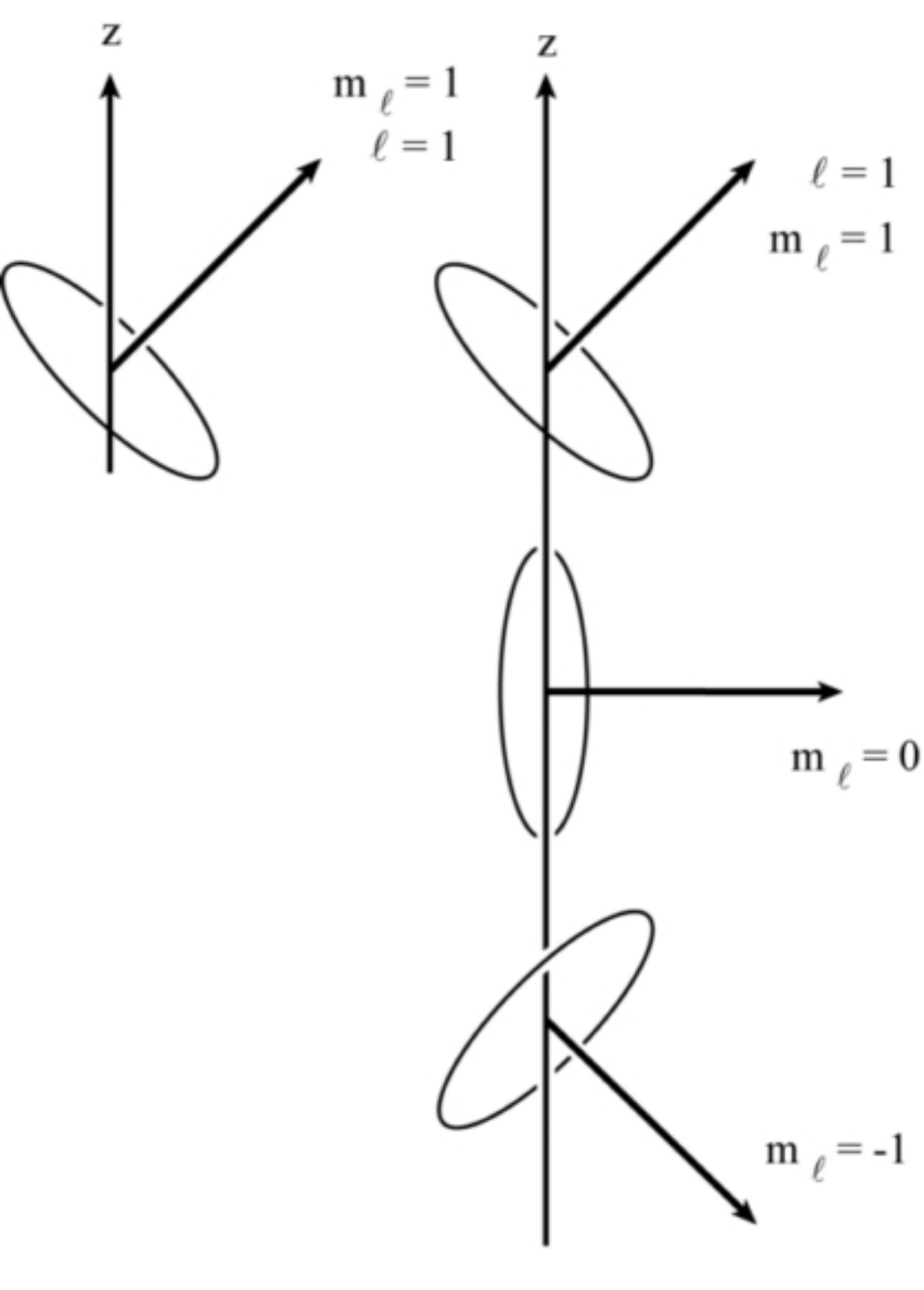


Configuration **Term**

Central field **Repulsion**

Numerical example for 2p3d in O V, energies in cm^{-1}

E(2p3d) =	701810	Kinetic and central part of electrostatic
ΔE (P - D) =	8980	Direct part of electrostatic repulsion
ΔE (^{1}F - ^{3}F) =	15074	Exchange part of electrostatic repulsion


z
m ℓ = 1
ℓ = 1
z
ℓ = 1
m ℓ = 1
m ℓ = 0
m ℓ = -1

Direct electrostatic interaction in a pp'config.

pp' contains a S, P and D term ($\ell_1 = \ell_2 = 1 \Rightarrow L = 0, 1, 2$)

D; $L = 2$:

L M_L ℓ m_ℓ

$$|1\ 1\ 2\ 2\rangle = |1\ 1\rangle \cdot |1\ 1\rangle$$

$$|1\ 1\ 2\ 1\rangle = \frac{1}{\sqrt{2}}|1\ 1\rangle|1\ 0\rangle + \frac{1}{\sqrt{2}}|1\ 0\rangle|1\ 1\rangle$$

$$|1\ 1\ 2\ 0\rangle = \frac{1}{\sqrt{6}}|1\ 1\rangle|1\ -1\rangle + \sqrt{\frac{2}{3}}|1\ 0\rangle|1\ 0\rangle + \frac{1}{\sqrt{6}}|1\ -1\rangle|1\ 1\rangle$$

$$|1\ 1\ 2\ -1\rangle = \frac{1}{\sqrt{2}}|1\ 0\rangle|1\ -1\rangle + \frac{1}{\sqrt{2}}|1\ -1\rangle|1\ 0\rangle$$

$$|1\ 1\ 2\ -2\rangle = |1\ -1\rangle \cdot |1\ -1\rangle$$

P; $L = 1$:

$$|1\ 1\ 1\ 1\rangle = \frac{1}{\sqrt{2}}|1\ 1\rangle|1\ 0\rangle - \frac{1}{\sqrt{2}}|1\ 0\rangle|1\ 1\rangle$$

Note!!

$$|1\ 1\ 1\ 0\rangle = \frac{1}{\sqrt{2}}|1\ 1\rangle|1\ -1\rangle - \frac{1}{\sqrt{2}}|1\ -1\rangle|1\ 1\rangle + 0 \cdot |1\ 0\rangle|1\ 0\rangle$$

$$|1\ 1\ 1\ -1\rangle = \frac{1}{\sqrt{2}}|1\ 0\rangle|1\ -1\rangle - \frac{1}{\sqrt{2}}|1\ -1\rangle|1\ 0\rangle$$

S; $L = 0$:

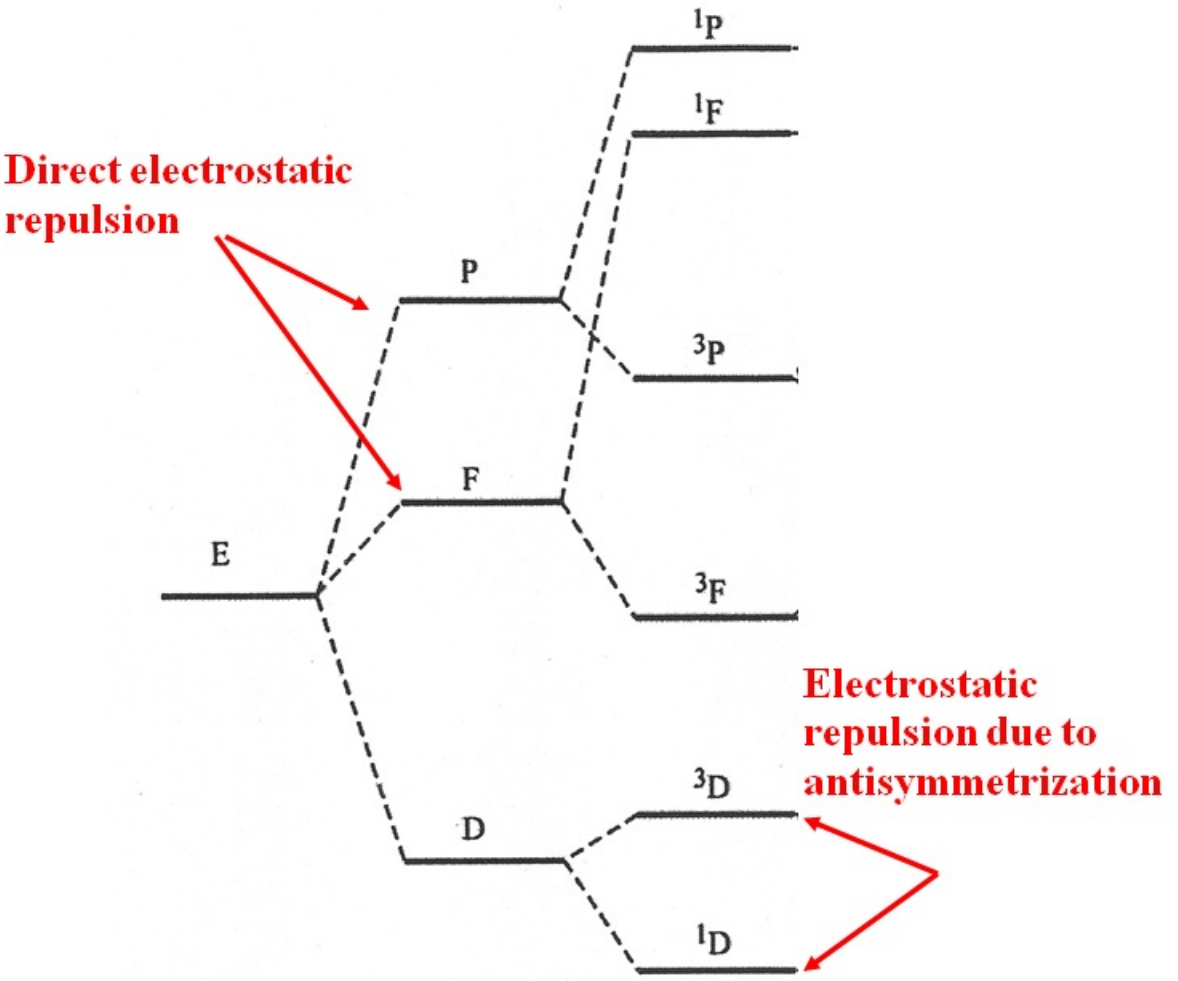
$$|1\ 1\ 0\ 0\rangle = \frac{1}{\sqrt{3}}|1\ 1\rangle|1\ -1\rangle - \frac{1}{\sqrt{3}}|1\ 0\rangle|1\ 0\rangle + \frac{1}{\sqrt{3}}|1\ -1\rangle|1\ 1\rangle$$

Combinations with maximum overlap between the charge distributions are marked in blue. Max overlap means max repulsion means less binding energy means higher excitation energy.

Thus, S and D terms tend to lay higher than P in *pp*'-configurations

Generally highest and lowest L terms tend to lay higher.

Details of the electrostatic interactions in a pd-configuration in LS-coupling



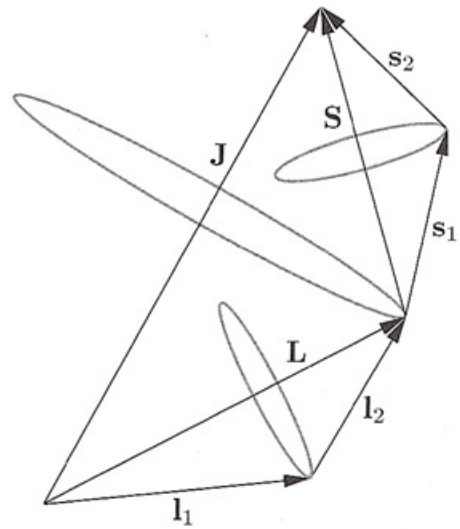
Angular momentum couplings of two electrons in open subshells

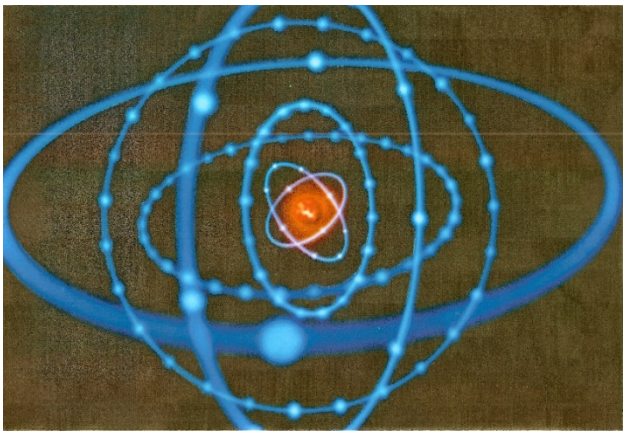
Energy structure	Angular momentum coupling	Wavefunctions	Eigenfunctions to
Configuration	-	$\left\|\ell_i, m_{\ell_i}\right\rangle \cdot \left\|s_i, m_{s_i}\right\rangle$	$\hat{\ell}_i^2,\ \hat{\ell}_{iz},\ \hat{s}_i^2,\ \hat{s}_{iz}$
Term $^{2S+1}$L	$\hat{L} = \hat{\ell}_1 + \hat{\ell}_2, \hat{S} = \hat{s}_1 + \hat{s}_2$	$\left\|L,\ M_L,\ S,\ M_S\right\rangle$	$\hat{L}^2,\ \hat{L}_z,\ \hat{S}^2,\ \hat{S}_z$
Level $^{2S+1}$L$_J$	$\hat{J} = \hat{L} + \hat{S}$	$\left\|L,\ S,\ J,\ M_J\right\rangle$	$\hat{L}^2,\ \hat{S}^2,\ \hat{J}^2, \hat{J}_z$

$$\left|\ell_i, m_{\ell_i}\right\rangle \cdot \left|s_i, m_{s_i}\right\rangle = R_{n_i\ell_i}(r_i) \cdot Y_{\ell_i m_{\ell_i}}(\theta_i, \varphi_i) \cdot \chi_{m_{s_i}}(sz_i)$$

Example of $\hat{L} = \hat{\ell}_1 + \hat{\ell}_2$ coupling using Clebsch-Gordan coeff.

$$\left|\ell_1, \ell_2, L, M_L\right\rangle = \sum_{m_{\ell_1}} C(\ell_1, m_{\ell_1}, \ell_2, M_L - m_{\ell_1} : L, M_L) \left|\ell_1, m_{\ell_1}\right\rangle \left|\ell_2, M_L - m_{\ell_1}\right\rangle$$





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Magnetic interactions - internal

$$E = \left\langle -\hat{\mu} \cdot \hat{B} \right\rangle_{\Psi}$$

Spin-Orbit interaction

$$\left.\begin{array}{l} \hat{\mu} = \hat{\mu}_S = -2\dfrac{e}{2m}\hat{S} \\ \hat{B} \sim \hat{L} \\ \Psi = |L,S,J,M_J\rangle \end{array}\right\} \Rightarrow E_{SO} = \sim < \hat{L}\cdot\hat{S} >_{\Psi} = \beta \cdot \frac{1}{2}\left[J(J+1) - L(L+1) - S(S+1)\right]$$

Landé: $E_{SO}(J) - E_{SO}(J-1) = \beta \cdot J$

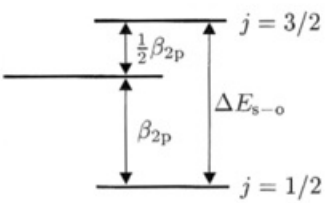
Hyperfine interaction (Note $m_p \approx 2000 \cdot m_e$)

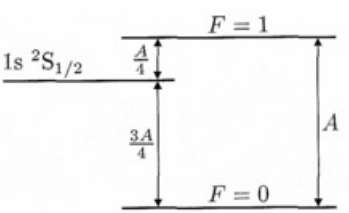
$$\left.\begin{array}{l} \hat{\mu} = \hat{\mu}_I = +g_I \dfrac{e}{2m_p}\hat{I} \\ \hat{B} \sim \hat{J} \\ \Psi = |J,I,F,M_F\rangle \end{array}\right\} \Rightarrow E_{hfs} = \sim < \hat{J}\cdot\hat{I} >_{\Psi} = A \cdot \frac{1}{2}\left[F(F+1) - J(J+1) - I(I+1)\right]$$

Landé: $E_{\mathrm{hfs}}(F) - E_{\mathrm{hfs}}(F-1) = A \cdot F$

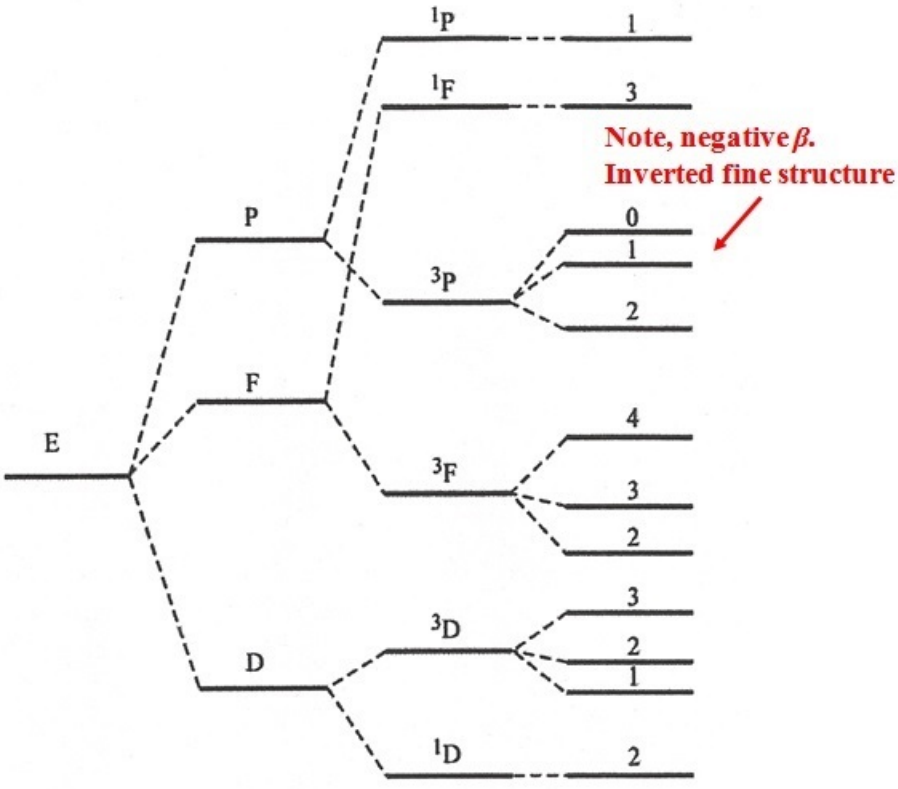
Scaling: $\beta_{\mathrm{H}} \sim \dfrac{Z^4}{n^3 \cdot \ell^3} \rightarrow \dfrac{\zeta^4}{(n^*)^3 \cdot \ell^3}, \quad n^* = n - \delta, \zeta = Z - N_{\mathrm{core}}$

$$A_{\mathrm{H}}(s) \sim \frac{Z^3}{n^3} \rightarrow \frac{\zeta^3}{(n^*)^3}$$





pd-configuration LSJ-coupling



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ΔE (^{1}F - ^{3}F) = 15074	Exchange part of electrostatic repulsion
ΔE ($^3F_4$- $^3F_3$) = 235	Spin-orbit magnetic energy

Magnetic interactions - external

Zeeman effect. (B ~ 1 T)

Weak field, i.e. much less energy than that of the SO-interaction

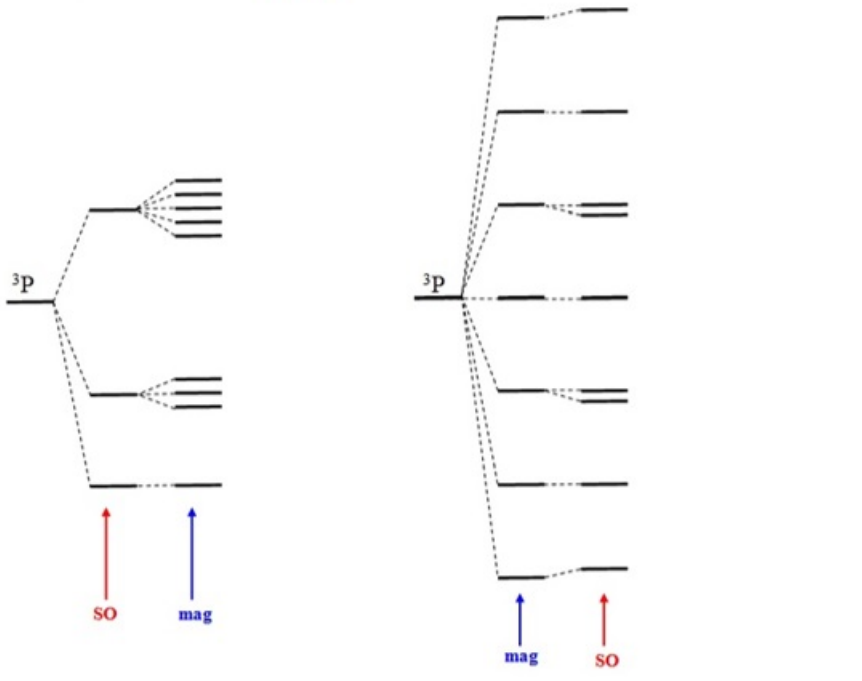
$$\left.\begin{aligned}\hat{\mu} &= \hat{\mu}_L + \hat{\mu}_S = -\frac{e}{2m}(\hat{L} + 2\hat{S}) \\ \hat{B} &= B_{ext} \cdot \hat{e}_z,\ \Psi = |L,S,J,M_J\rangle\end{aligned}\right\} \Rightarrow E(L,S,J,M_J) = E(L,S,J) + \mu_B \cdot B \cdot g_J \cdot M_J$$

Paschen-Back effect. (B ~ 1000 T)

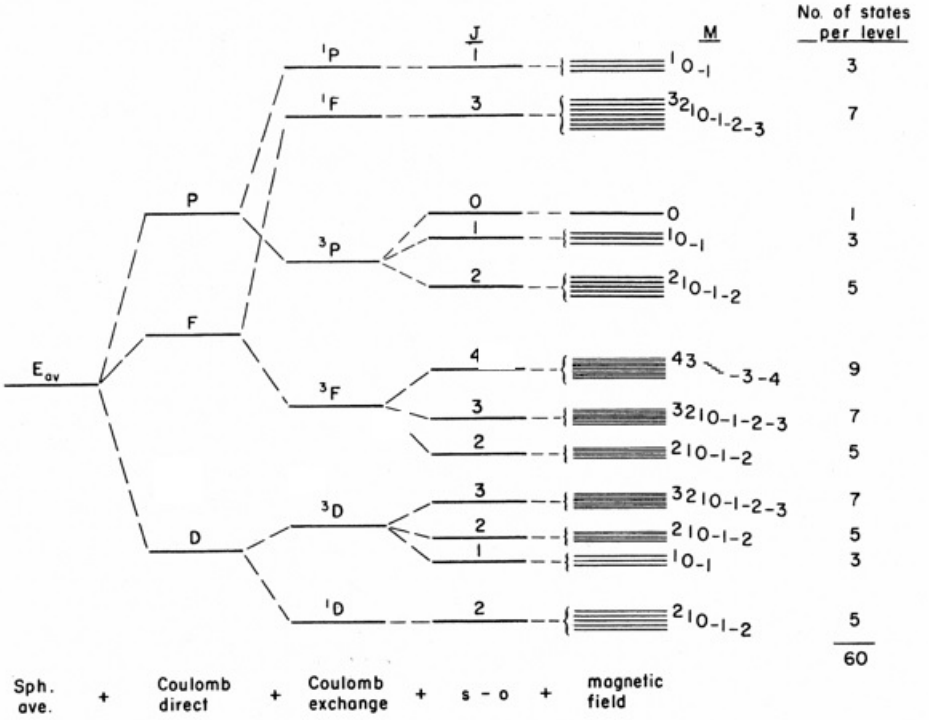
Strong field, i.e. much more energy than that of the SO-interaction.

$$\left.\begin{aligned}\hat{\mu} &= \hat{\mu}_L + \hat{\mu}_S = -\frac{e}{2m}(\hat{L} + 2\hat{S}) \\ \hat{B} &= B_{ext} \cdot \hat{e}_z,\ \Psi = |L,M_L,S,M_S\rangle\end{aligned}\right\} \Rightarrow E(L,M_L,S,M_S) = E(L,S) + \mu_B \cdot B \cdot (M_L + 2M_S)$$

Then SO as the next perturbation, $\beta \cdot M_L M_S$



pd-configuration with external magnetic field



Configuration **Term** **Level** **State**

Central field **Repulsion** **Spin-orbit** **External B-field**

Numerical example for 2p3d in O V, energies in cm^{-1}

E(2p3d) = 701810	Kinetic and central part of electrostatic
ΔE (P - D) = 8980	Direct part of electrostatic repulsion
ΔE (^{1}F - ^{3}F) = 15074	Exchange part of electrostatic repulsion
ΔE ($^3F_4$- $^3F_3$) = 235	Spin-orbit magnetic energy
$\Delta E_{mag} = g_J \cdot \mu_B \cdot B$ = 0.5	B = 1 T, g_J = 1, ΔM_J = 1. Indep. of atom

Magnetic interactions

General: $$E = \langle -\boldsymbol{\mu} \cdot \mathbf{B} \rangle_{\Psi}$$

Where **μ** is a magnetic moment and **B** the magnetic field strengt

Spin-Orbit interaction. $J = L + S$

$$\left.\begin{array}{l} \boldsymbol{\mu} = \boldsymbol{\mu}_S = -2\dfrac{e}{2m}\mathbf{S} \\ \mathbf{B} \sim \mathbf{L} \end{array}\right\} \Rightarrow E_{SO} \sim <\mathbf{L}\cdot\mathbf{S}> = \beta \cdot \frac{1}{2}\left[J(J+1) - L(L+1) - S(S+1)\right]$$

Hyperfine interaction (Note $m_p \approx 2000 \cdot m_e$). $F = J + I$

$$\left.\begin{array}{l} \boldsymbol{\mu} = \boldsymbol{\mu}_I = +g_I\dfrac{e}{2m_p}\mathbf{I} \\ \mathbf{B} \sim \mathbf{J} \end{array}\right\} \Rightarrow E_{hfs} \sim <\mathbf{J}\cdot\mathbf{I}> = A \cdot \frac{1}{2}\left[F(F+1) - J(J+1) - I(I+1)\right]$$

Zeeman effect. (B ~ 1 T)

Weak field, i.e. much less energy than that of the SO-interaction

$$\left.\begin{array}{l} \boldsymbol{\mu} = \boldsymbol{\mu}_L + \boldsymbol{\mu}_S = -\dfrac{e}{2m}(\mathbf{L} + 2\mathbf{S}) \\ \mathbf{B} = \mathbf{B}_{\text{ext}},\ \Psi = |L, S, J, M_J\rangle \end{array}\right\} \Rightarrow E(L,S,J,M_J) = E(L,S,J) + \mu_B \cdot B \cdot g_J \cdot M_J$$

Paschen-Back effect. (B ~ 1000 T)

Strong field, i.e. much more energy than that of the SO-interaction.

$$\left.\begin{array}{l} \boldsymbol{\mu} = \boldsymbol{\mu}_L + \boldsymbol{\mu}_S = -\dfrac{e}{2m}(\mathbf{L} + 2\mathbf{S}) \\ \mathbf{B} = \mathbf{B}_{\text{ext}},\ \Psi = |L, M_L, S, M_S\rangle \end{array}\right\} \Rightarrow E(L,M_L,S,M_S) = E(L,S) + \mu_B \cdot B \cdot (M_L + 2M_S)$$

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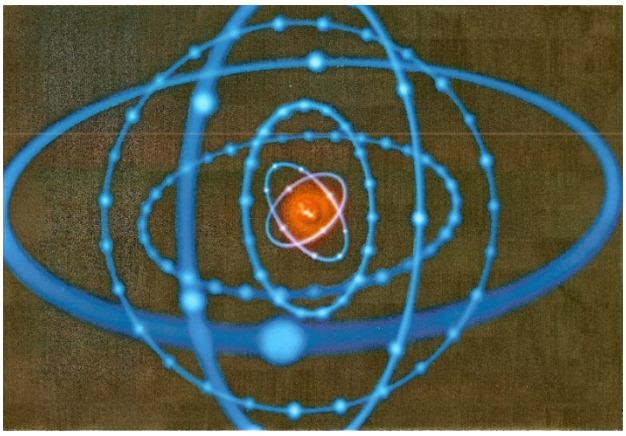


- **One electron atoms, H-like.**

  Bohr model

  Exact quantum mechanical results

- **Hydrogenic-, Rydberg-atoms. Quantum defect**

  Accurate semi-empirical results

- **Many electron atoms.**

  Approximations CFA + LS/jj- coupling

- **Magnetic interactions**

  Spin-orbit, Hyperfine and

  External mag. fields

- **Transitions**

  Selection rules and line widths

- **Molecules**

E1 Selection Rules

Only <u>one</u> electron may change n and ℓ quantum numbers, i.e. orbital.

$\Delta \ell = \pm 1$

$\Delta J = 0, \pm 1$ **not 0 to 0**

***<u>LS</u>*-coupling**

$\Delta S = 0$

$\Delta L = 0, \pm 1$ **not 0 to 0**

***jj*-coupling**

$\Delta j_1 = 0$

$\Delta j_2 = 0, \pm 1$ **not 0 to 0**

With hyperfine structure also

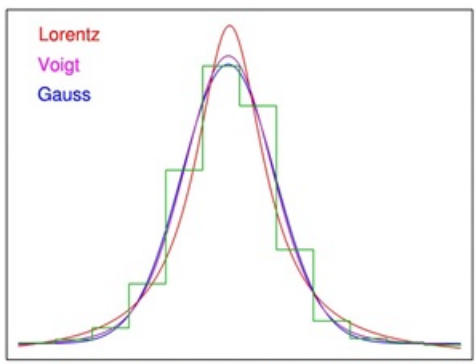
$\Delta F = 0, \pm 1$ **not 0 to 0**

In an external magnetic field

$\Delta M_J = 0, \pm 1$ **not 0 to 0 if** $\Delta J = 0$

Line widths and profiles

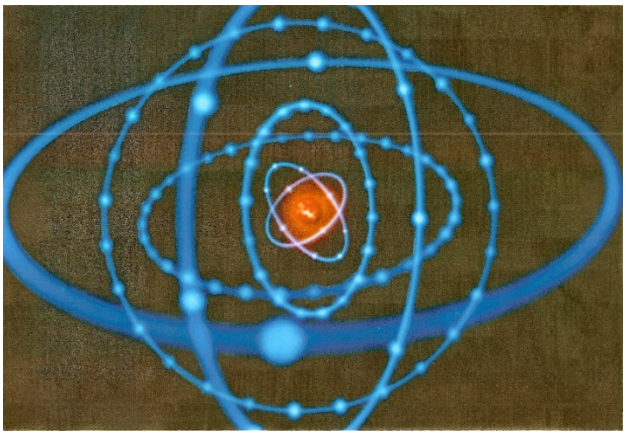
In the atom	**Natural**	**Lorentz**
In the light source	**Collisional**	**Lorentz**
	Power	**Lorentz**
	Self absorption	**---**
	Doppler	**Gauss**
In the detector	**Instrumental**	**Appox. Gauss**



Voight = convolution of Lorentz and Gauss

Na-example
(3s - 3p 5890 Å, lifetime 16 ns)

Broadening	Δf / GHz	$\Delta\lambda$ / Å
Natural	0.01	0.0001
Power, $I = 170$ mW/cm^2	0.054	0.0006
Pressure, $p = 0.1$ atm	0.084	0.0009
Doppler (600 K)	1.86	0.022
Instrument. Fabry Perot: $d = 1$ cm, $R = 0.9$	0.25	0.003
Instrument. Grating 1200 ℓ/mm, 50 μm slit	30	0.35



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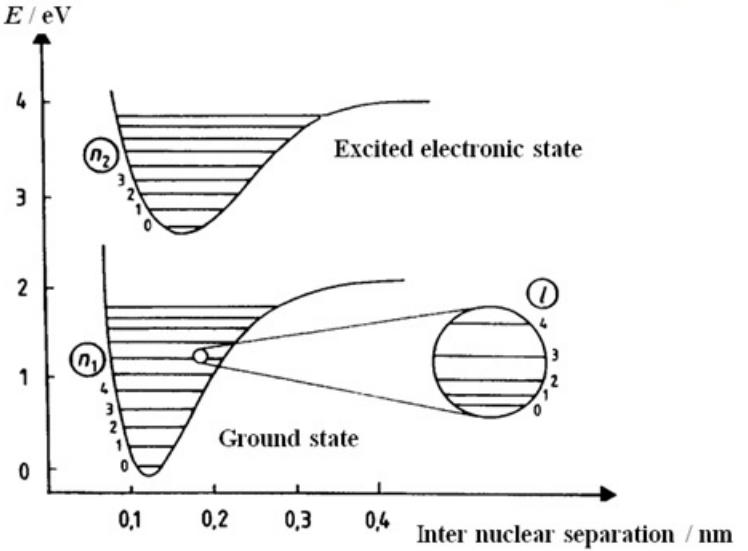
Energies in a Diatomic Molecule - Summary.

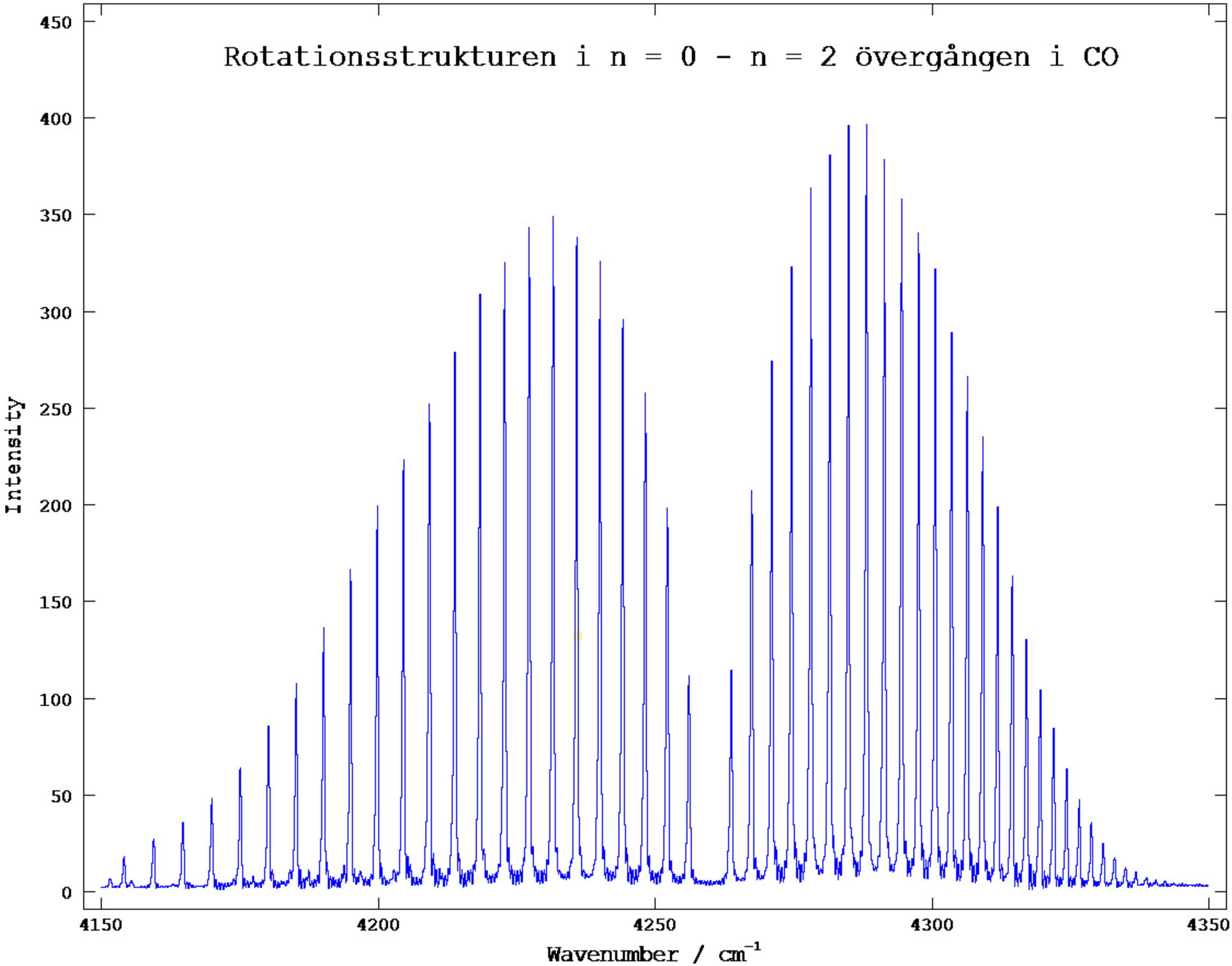
$$E = E_{elektron} + E_{vib} + E_{rot} = E_{elektron} + \hbar\omega_0(v + \frac{1}{2}) + \frac{\hbar^2}{2\mu r^2} \cdot \ell(\ell+1)$$



Orders of magnitude

	Electron	Vibration	Rotation
E / cm^{-1}	40000	1500	10
E / eV	5	0.2	0.001
λ / μm	0.3	6	1000
T / K	40000	1500	10

(Note the coincidence that energies expressed in cm^{-1} and as a temperature in K has almost the same numerical value, i.e. $1/(100 \cdot h \cdot c) = 5.035 \cdot 10^{22} \approx 2/(3 \cdot k) = 4.83 \cdot 10^{22}$!)


Rotationsstrukturen i n = 0 - n = 2 övergången i CO
Intensity
450
400
350
300
250
200
150
100
50
0
4150
4200
4250
4300
4350
Wavenumber / cm^{-1}

The Greenhouse Effect.

The black-body radiation from the Sun (5500 °C) and the Earth (18 °C) and the absorption in the atmosphere in different wavelength regions