The Zeeman-Effect

Some Basics

- <u>Quantum numbers (qn)</u>

n = 1, 2, 3, … main qn (energy states -shell)

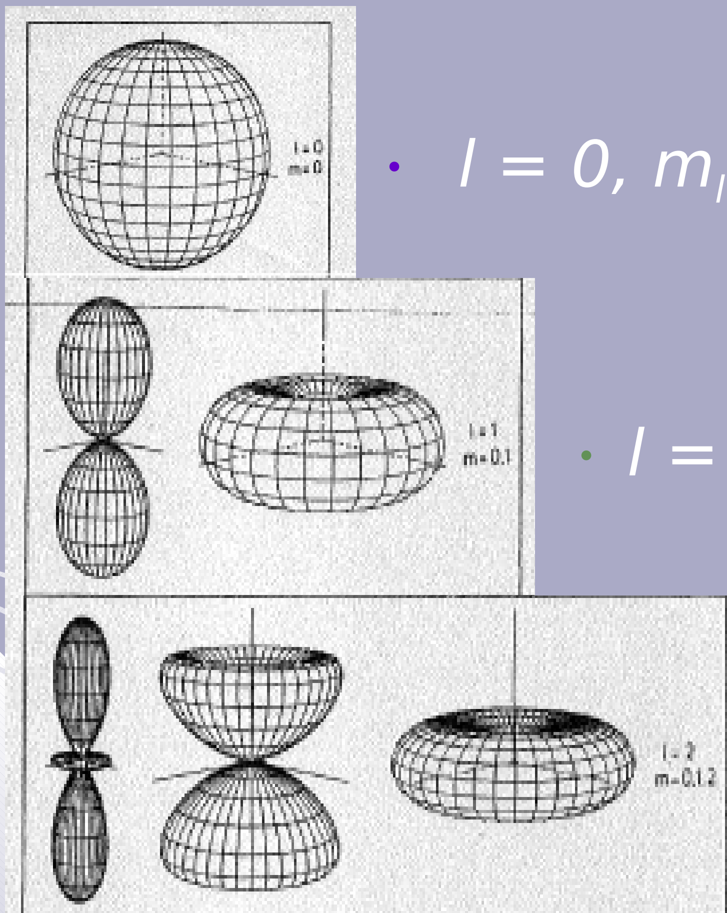
l = 0, 1, … (n-1) orbital angular momentum (s, p, d, …-subshell)

m_l = -l, …, +l magnetic qn, projection of l (energy shift)

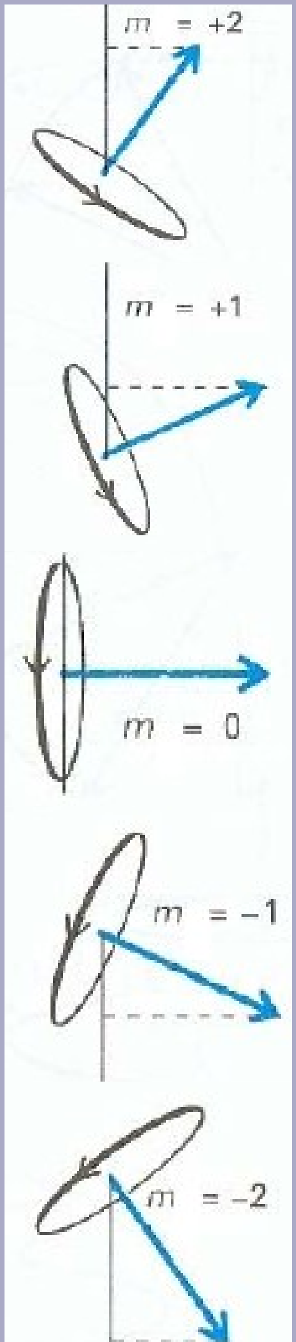
m_s = ±½ spin angular momentun

$j = |l-s| \leq j \leq l+s$ total angular momentum (if coupled, interactions of spin-orbit dominate over *B*)

Some Basics



- $l = 0, m_l = 0$
  - $l = 1, m_l = 0, 1$
    - $l = 2, m_l = 0, 1, 2$



Some Basics

- more than 1 e^-

$$n^{2S+1}L_J$$

$L = \Sigma\, l_i$ (S, P, D, …)

$S = \Sigma\, s_i$

$J = \Sigma\, j_i$ (with m_J)

Eigenvalues:

$L = \hbar\, [l\ (l+1)]^{½}$

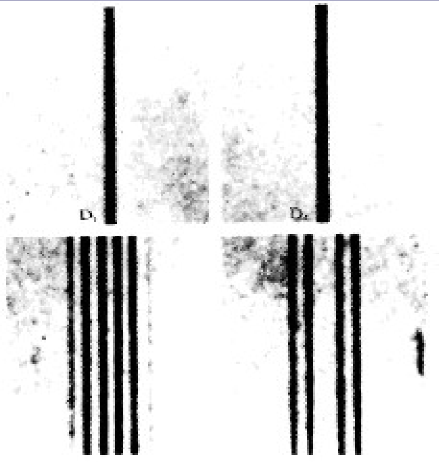
$S = \hbar\, [s\ (s+1)]^{½}$

$J = \hbar\, [j\ (j+1)]^{½}$

Zeeman Effect

- discovered 1896 different splitting patterns in different spectral lines
- splitted lines are polarized
- splitting proportional to magnetic field
  $\Delta\lambda \sim g_L \lambda^2 B$
- Interaction of atoms with external magnetic field due to magnetic moment m_j

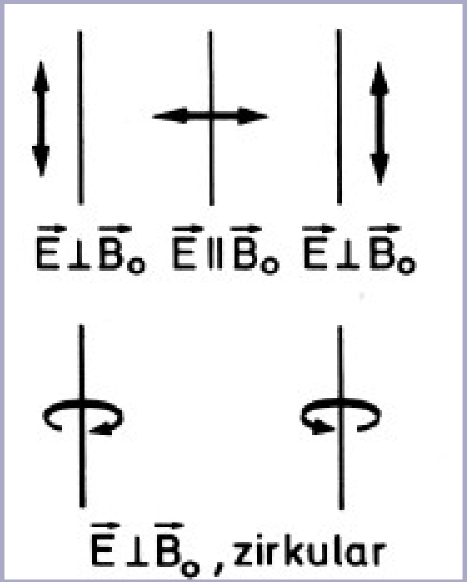
P. Zeeman



Zeeman Effect

- normal Zeeman effect:
  S = 0, *L* = *J* ≠ *0*
- **split in 3 components**
  components with $\Delta m_J = 0$ (π)
  components with $\Delta m_J = -1$ and $+1$ (± σ)

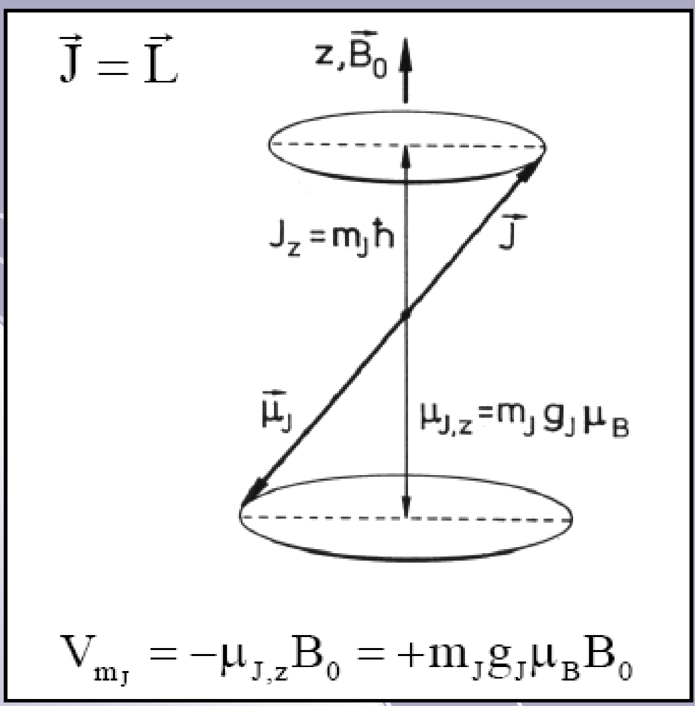
  - **2 possibilities:**
    - ***B* parallel to line of sight**
      ➔ two σ circular polarized
    - ***B* perpendicular to line of sight**
      ➔ two σ polarised vertical to field
      one π polarised horizontal to field



Zeeman Effect

$$V = -\vec{\mu} \bullet \vec{B}$$

$$\vec{\mu}_j = g_j \frac{e_0}{2m_e} \vec{j}$$



- interaction with external field
  - magnetic momentum of Atom

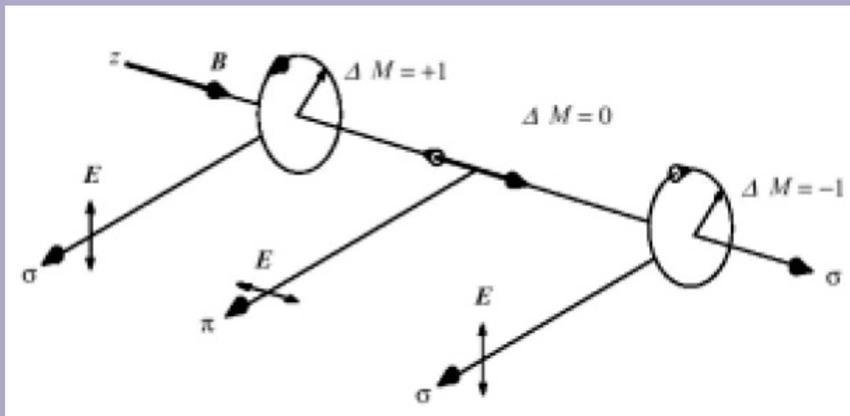
$$g_J = 1 + \frac{J(J+1) + S(S+1) - L(L+1)}{2J(J+1)}$$

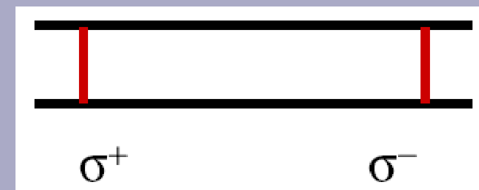
- ***J* and μ_J antiparallel**
  since S=0 and $L=J$ ➔ $g_J = 1$
  ➔ only 3 values of Δm possible:
  0, ± 1 ➔ π, ± σ

$\mu_B = (e\hbar)/(2m_e)$ Bohr magneton

➔ $V = m_J \mu_B B_0$

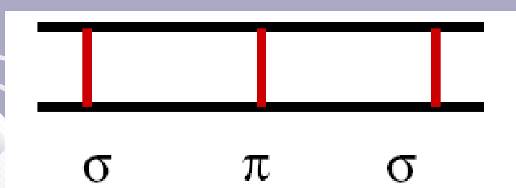
Zeeman Effect

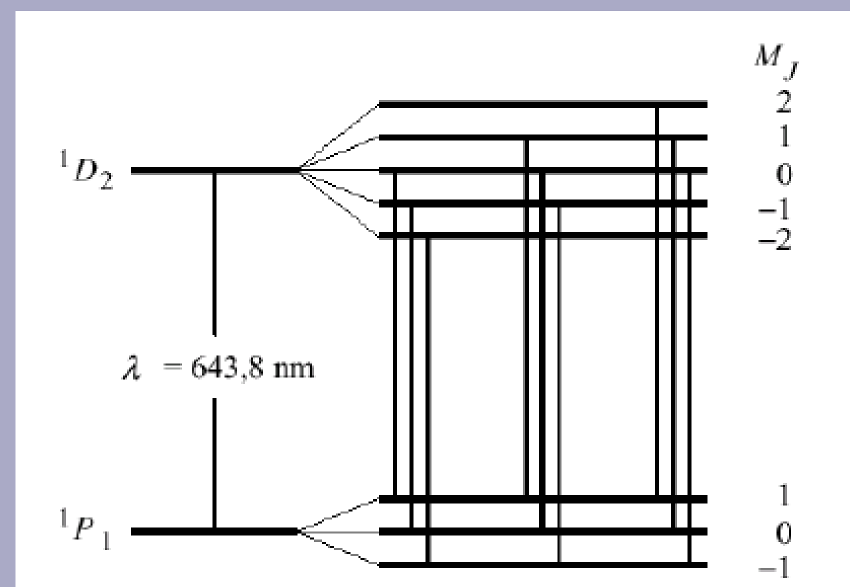




- Selection rules:

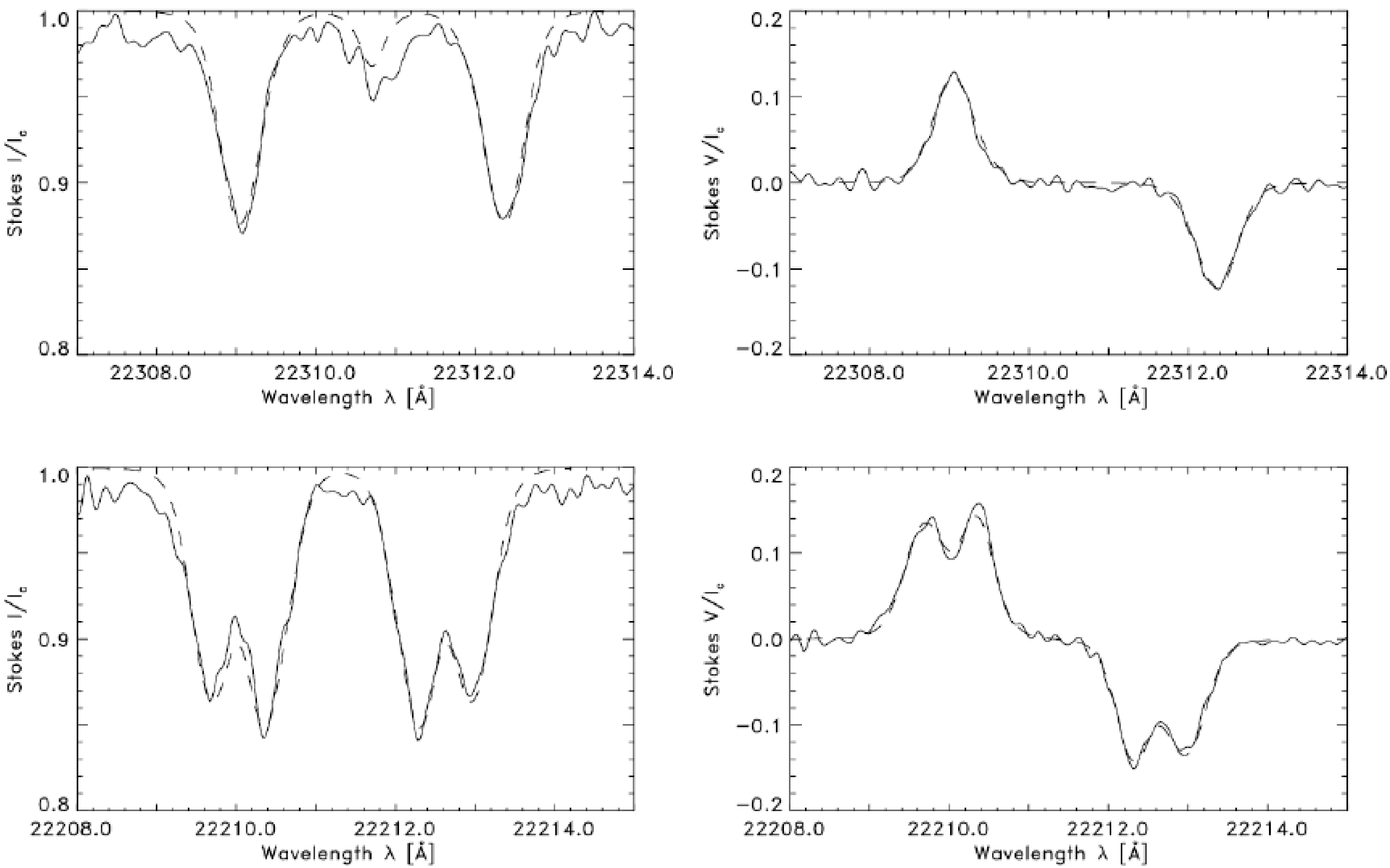
$\Delta L = \pm 1$ $\Delta M = 0, \pm 1$





- fine-structure dependening on n, j

Fully Split Titanium Lines at 2.2μm



Rüedi et al. 1998

Anormal Zeeman Effect

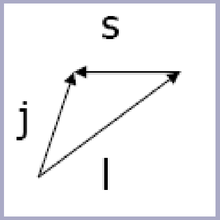
- anormal Zeeman effect (LS – coupling):

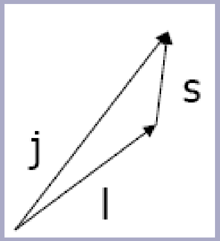
  $S \neq 0$, $L \neq 0$ ➔ usual case

$$\vec{j} = \vec{l} + \vec{s}$$

j=1+1/2=3/2

j=1-1/2=1/2





  – **J and μ_J not antiparallel**

    $g_J \neq 1$

    ➔ $\Delta E = g_J \, \Delta m_J \, \mu_J \, B$

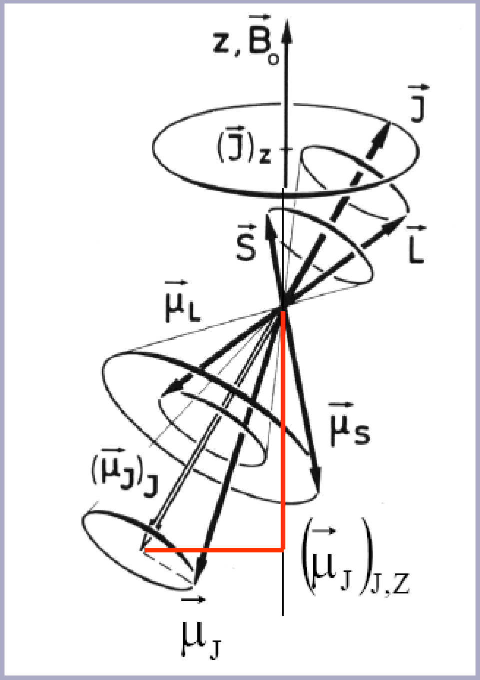
    more different energy levels

    ➔ more components possible

$$\vec{\mu}_L = -g_L \frac{\mu_B}{\hbar} \vec{L}$$

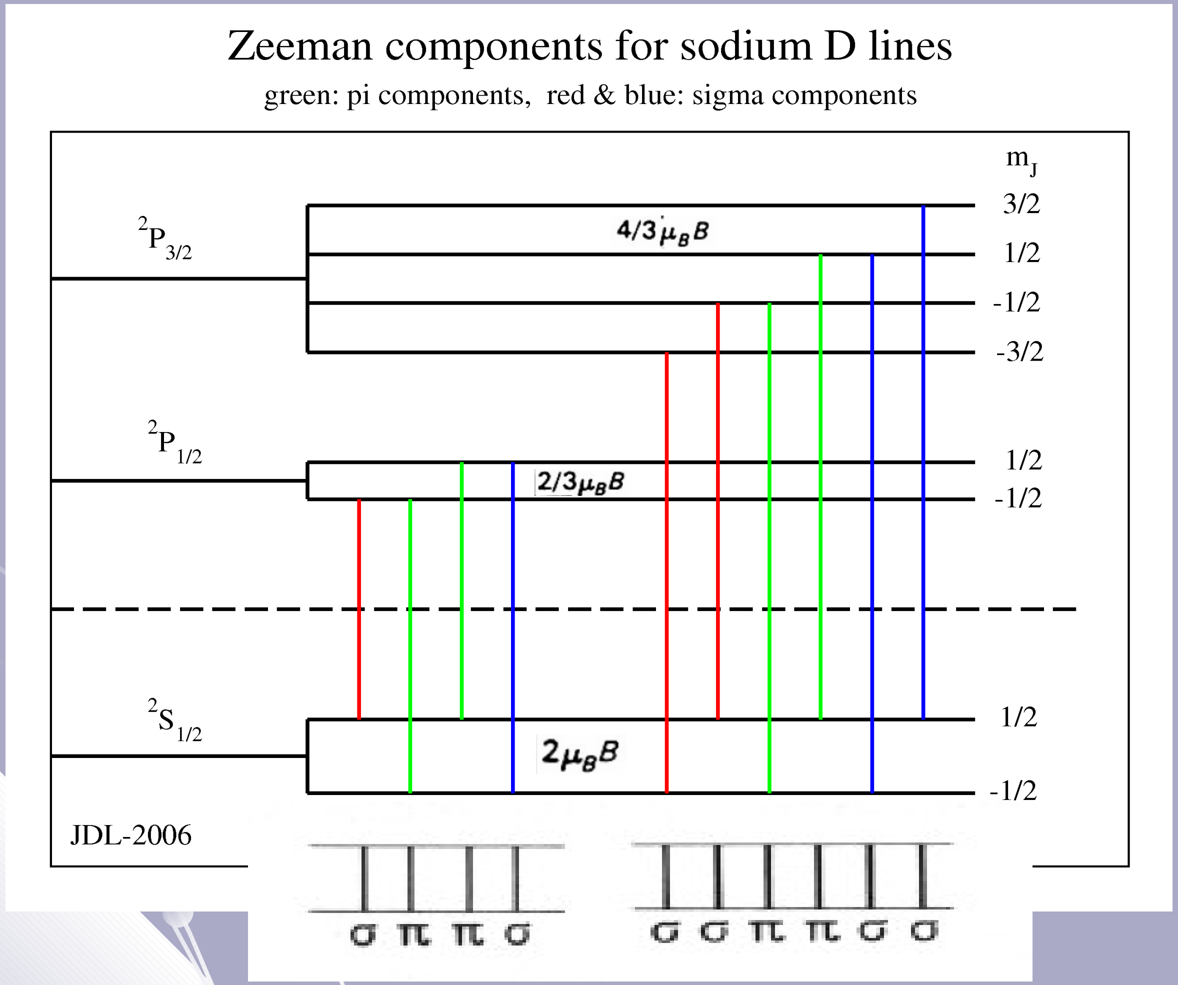
$$\vec{\mu}_S = -g_S \frac{\mu_B}{\hbar} \vec{S}$$

$$\vec{\mu}_J = \vec{\mu}_L + \vec{\mu}_S$$



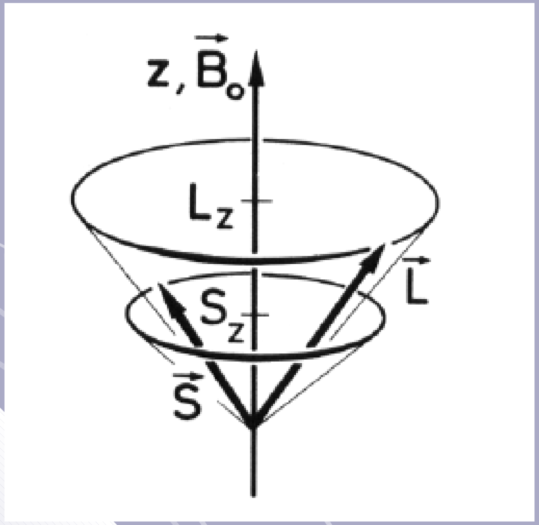
Anormal Zeeman Effect

$$n\,^{2S+1}L_J$$



Paschen-Back Effect

- **for most transitions and B < 50000 G (5 T = upper limit for main sequence stars) lines are in Zeeman regime**
- if $|\vec{B}_0| > |\vec{B}_J|$ *L* and *S* decouple ➔ Paschen-Back effect



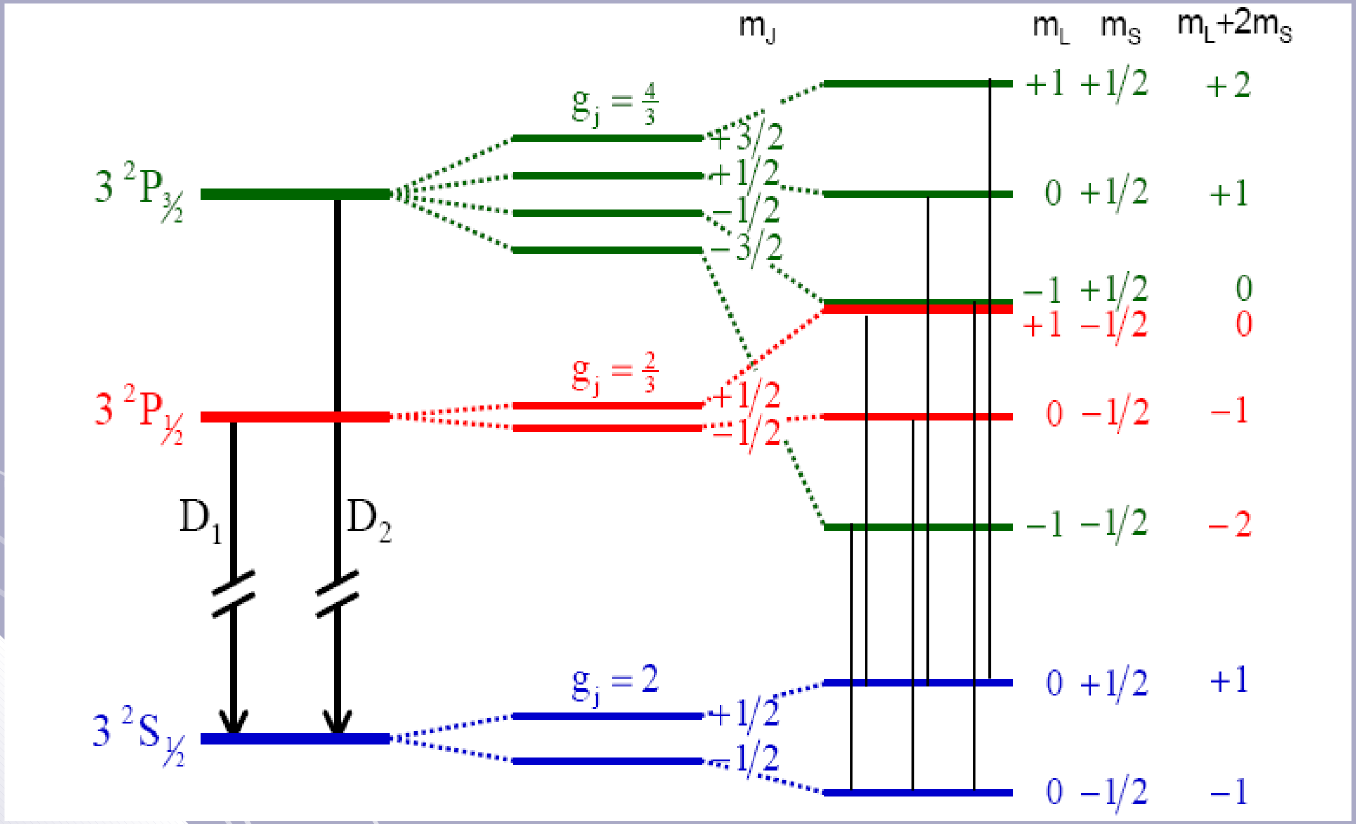
$$V_{m_S,m_L} = (m_L + 2m_S)\mu_B B_0$$
$$\Delta E = (\Delta m_L + 2\Delta m_S)\mu_B B_0$$

Paschen-Back Effect

weak field

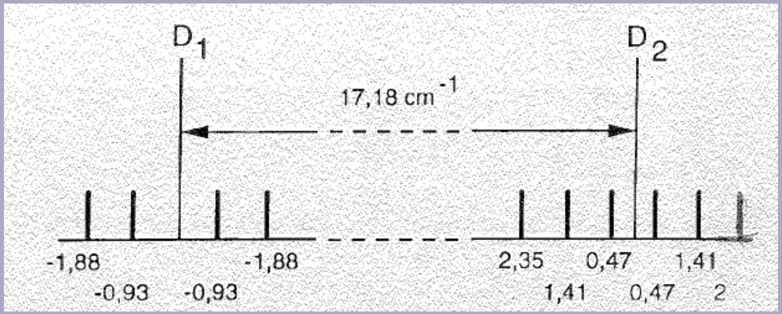
strong field

$\Delta m_L = 0, \pm 1$
$\Delta m_S = 0$



Paschen-Back Effect

- fine structure splitting varies a lot in atoms, so a few lines may be in Paschen-Back regime at much smaller B value than others.



- Zeeman splitting for sodium D_1 and D_2 in a field of 3 T
- splitting for Li: 0.3 cm^{-1}

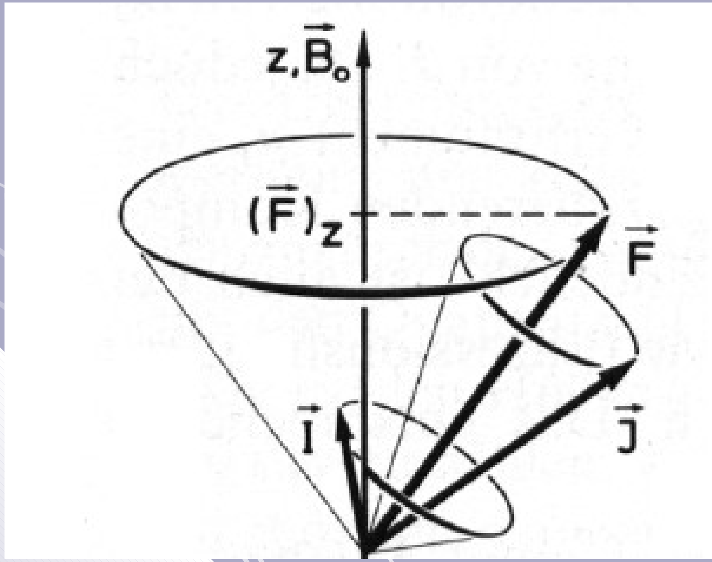
➔ 3 T is a strong field for Li but a weak field for Na
Na shows Zeeman splitting
Li would show Paschen-Back splitting

Hyperfine structure

- fields of $B_0 \geq 0.1$ T often cause splitting
- magnetic momentum of a proton due to its spin:

$$\vec{\mu}_I = \frac{e_0}{2m_p}\vec{I}$$

I … spin of nucleus

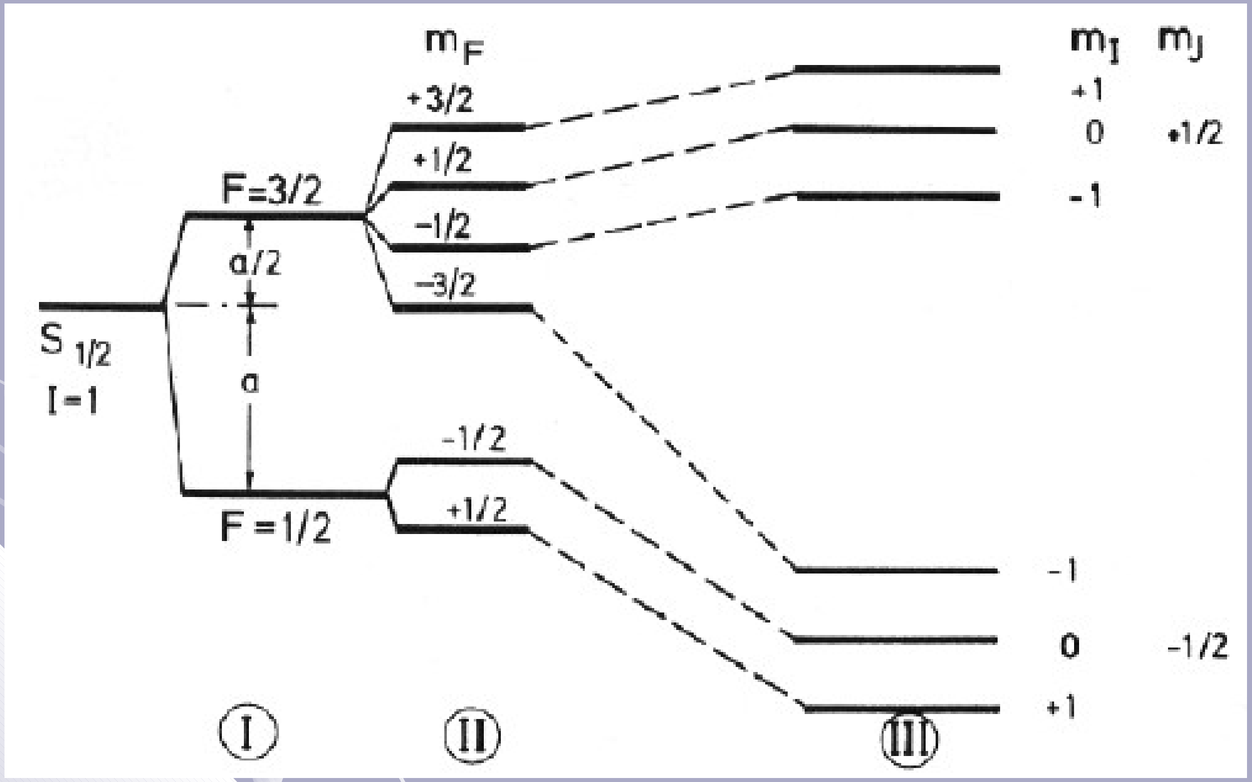


➔ $F = J + I$ spin coupling

$m_F = -F, F-1, \ldots, +F$

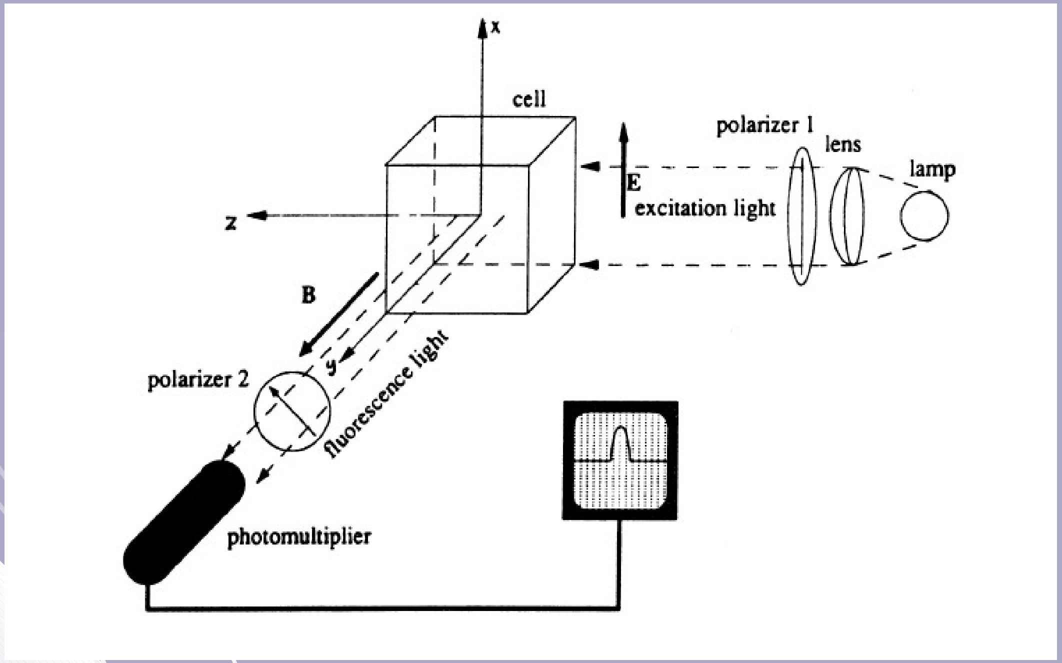
Hyperfine structure

- for stronger fields ➔ lines in the Paschen-Back regime



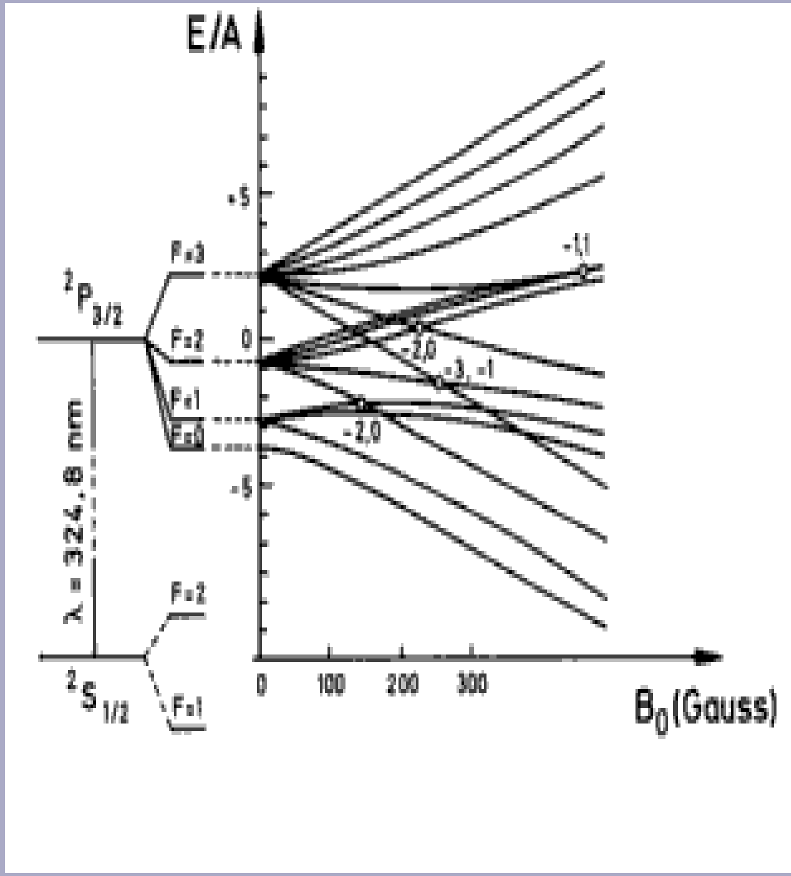
Hanle effect

- classical explanation:
  mercury atoms in absorption-cell – polarized light excites e^- damped oscillation until e^- is ground state (lifetime of upper state) – emits polarised light (fluorescence resonance) – depending on observing angle light is not always visible – if external B_0 present ==> intensity of fluorescence resonance changes (= **Hanle effect**)

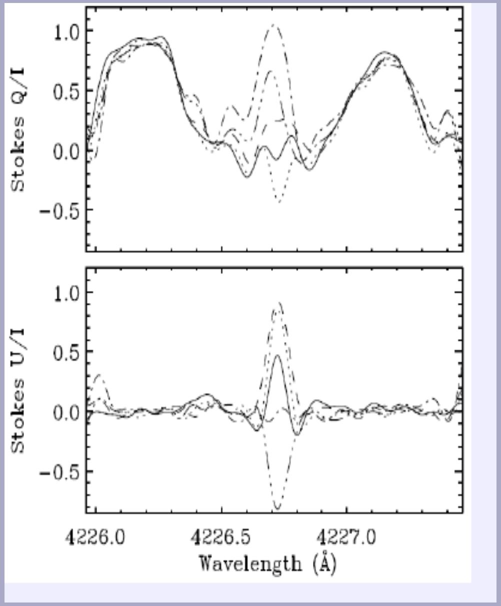


Hanle effect

- <u>quantum mechanical explanation:</u> **level-crossing spectroscopy**
- a Zeeman sublevel (energy decreases with increasing B_0) may cross with another magnetic sublevel from a lower state (energy increases with increasing magnetic field)
- if atoms excited coherently at fields corresponding to crossing points, changes of fluorescence intensity
- → “non-zero field level crossing” occurs in atoms that already show hyperfine structure without an external B_0.



Hanle effect



- unpolarised light is scattered through ~90^o
  scattered beam is linearly polarised perpendicular to scattering plane

- if scattering atom is in magnetic field
  J vector precesses with period of *4πmc/eB* (Lamor frequency)

- if this frequency is comparable to the decay lifetime of upper state, the polarisation plane of re-emitted photon will be rotated from non-magnetic case

- Intensity of the fluorescent light proportional to B ==> allows detection of weak fields (<10G) in situations with large-angle scattering

Applications