$\frac{\hbar}{i}\vec{\nabla} - q\vec{A}$ $\qquad i\hbar\frac{\partial}{\partial t} - qV$ $\qquad$ couplage minimal

Dirac: $\vec{p} \to \vec{p} - q\vec{A}$

$$i\hbar\frac{\partial\Psi}{\partial t} = \left[c\,\vec{\alpha}\cdot\vec{p} + \beta mc^2\right]\Psi$$

$$\vec{\alpha} = \begin{pmatrix} 0 & \vec{\sigma} \\ \vec{\sigma} & 0 \end{pmatrix} \qquad \beta = \begin{pmatrix} I' & 0 \\ 0 & -I' \end{pmatrix}$$

$$\vec{\sigma}\cdot\vec{B}$$

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2.2 Magnétisme classique
2.3 " quantique
2.4 " dans les atomes
- Dirac, H de Pauli
- Couplage S.O.

2.5 Paramagnétisme (Van Vleck), diamagnétisme
2.6 Structure fine (règles de Hund)
hyperfine, effets QED (Lamb)
2.7 Environnements: champs cristallins
effet Jahn-Teller

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$$\mathcal{H} = \left[mc^2 + \frac{1}{2m}(\vec{p} - q\vec{A})^2 - \overset{\text{néglige}}{\frac{p^4}{8m^3c^2}}\right] + qV - \overset{\text{Zeeman}}{\frac{q\hbar}{2m}\vec{\sigma}\cdot\vec{B}}$$

$$-iq\frac{\hbar^2}{8m^2c^2}\vec{\sigma}\cdot\underbrace{\vec{\nabla}\times\vec{E}}_{0} - \underbrace{\frac{q\hbar}{4m^2c^2}\vec{\sigma}\cdot(\vec{E}\times\vec{p})}_{\text{s.o.}} - \frac{q\hbar^2}{8m^2c^2}\vec{\nabla}\cdot\vec{E}$$

$\mu_B = \frac{\hbar e}{2m}$, $\quad \vec{\nabla}\times\vec{E} = -\frac{\partial\vec{B}}{\partial t}$, $\quad$ Darwin néglige

$\nabla\cdot E = -\nabla^2 V$ $\qquad$ Compton

$q\langle x^2\rangle\nabla^2 V$ $\qquad X \sim \frac{\hbar}{mc}$

Zitterbewegun

$$-q\frac{\hbar}{4m^2c^2}\vec{\sigma}\cdot\left(-\frac{\vec{r}}{|r|}\frac{\partial V}{\partial r}\times\vec{p}\right) \qquad \frac{10^{-34}}{10^{-30}\,10^{8}}$$

$$+q\frac{\hbar}{4m^2c^2}\frac{\partial V}{\partial r}\frac{1}{|r|}\vec{\sigma}\cdot(\vec{r}\times\vec{p})$$

$$\underbrace{q\frac{\hbar^2}{2m^2c^2}\frac{\partial V}{\partial r}\frac{1}{|r|}}\left(\vec{S}\cdot\vec{L}\right) = \lambda\vec{S}\cdot\vec{L} \qquad \lambda > 0$$

$$\frac{\partial V}{\partial r} < 0 \qquad q < 0$$

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Final $\quad \frac{\vec{B}\times\vec{r}}{2} = \vec{A}$

$$\boxed{\mathcal{H} = \mathcal{H}_0 + \mu_B(\vec{L} + g\vec{S})\cdot\vec{B} + \frac{e^2}{8m}\sum_i(\vec{B}\times\vec{r}_i)^2 + \lambda\sum_{i=1}^{Z}\vec{L}_i\cdot\vec{S}_i} \quad \text{Approx.}$$

$\vec{J}, \vec{L}, \vec{S}$ $\qquad$ Soit $|0\rangle$ fond. en l'absence de B

$\langle 0|\mathcal{H}_0|0\rangle$

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$$\langle 0|\underbrace{\mu_B(\vec{L} + g\vec{S})\cdot\vec{B}}\, + \frac{e^2}{8m}\underbrace{\sum_i(\vec{B}\times\vec{r}_i)^2}_{\text{diam.}}|0\rangle$$

$|\Psi\rangle = |0\rangle + \mathcal{O}(B)|1\rangle$ . . . .

$$\langle 0|\mu_B(\vec{L} + g\vec{S})\cdot\vec{B}|0\rangle$$

ex: $\vec{S} = \frac{1}{2}$ $\quad \vec{L} = 0$

$$Z = e^{-\beta(\mu_B g B)/2} + e^{\beta(g\mu_B B)/2}$$

$F = -N k_B T \ln Z$ $\qquad$ Helmholtz

$M = \left(\frac{\partial F}{\partial B}\right)\frac{1}{V}$ $\quad$ . . . . $E = F + TS$, $\quad E = -\frac{\partial \ln Z}{\partial\beta}$

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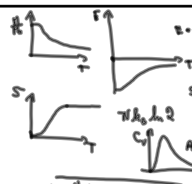


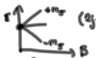
$E = -\vec{M}\cdot\vec{B}$

$S = \int\frac{C_v}{T}dT$

$N k_B \ln 2$ $\qquad C_v = T\frac{\partial S}{\partial T}$

Anomalie de Schottky

Soit les états propres caractérisés par $\vec{J}$



$(2j+1)$

$$\chi = \frac{\partial M}{\partial H} = \frac{n\mu_0\,\mu_{eff}^2}{3k_BT} \quad / \text{ pour } k_BT \gg \mu_B B$$

$\mu_{eff} = g_J\,\mu_B\sqrt{J(J+1)}$ $\qquad \sum_{m=-J}^{J} m^2$

facteur de Landé

$$\boxed{g_J = \frac{3}{2} + \frac{S(S+1) - L(L+1)}{2J(J+1)}}$$

$$\langle 0|\underbrace{\mu_B(\vec{L} + g\vec{S})}_{\vec{\mu}}|0\rangle\cdot\vec{B}$$

$$\langle 0|\vec{\mu}|0\rangle\cdot\vec{B} = g_J\,\mu_B\langle 0|\vec{J}|0\rangle\cdot\vec{B}$$

Wigner-Eckart

$\vec{J} = \vec{L} + \vec{S}$

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$$\langle 0| \frac{e^2B^2}{8m}\sum_{i=1}^{Z}(x_i^2+y_i^2)|0\rangle = \Delta E_0$$

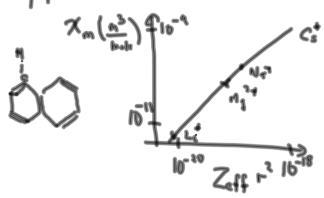
$$\vec B\times\vec r_i = \begin{vmatrix}\hat x & \hat y & \hat z\\ 0 & 0 & B\\ x_i & y_i & z_i\end{vmatrix} = \hat x(By_i) + \hat y(Bx_i)$$

$$\langle x_i^2\rangle = \frac{1}{3}\langle r_i^2\rangle$$

$$\Delta E_0 = \frac{e^2B^2}{12m}\sum_{i=1}^{Z}\langle r_i^2\rangle$$

$$M = -\frac{\partial E}{\partial B} \qquad \chi = \frac{\partial M}{\partial B}$$

NaF NaCl NaBr ... Na^+



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$$\langle M\rangle = \mu_B \tanh\left(\frac{\mu_B B}{k_BT}\right) \sim \boxed{\text{Curie} \quad \frac{\mu_B^2 B}{k_BT}}$$

$$\frac{\partial M}{\partial B} \sim \frac{\mu_B^2}{k_BT} \sim \chi > 0 \quad \text{paramagn.}$$

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$$\langle\Psi|\mathcal{H}_1|\Psi\rangle = \langle 0|\mathcal{H}_1|0\rangle + \langle\Psi_1|\mathcal{H}_1|0\rangle + \langle 0|\mathcal{H}_1|\Psi_1\rangle$$

$$\mathcal{H}_0|m\rangle = E_m|m\rangle$$

$$(\mathcal{H}_0+\mathcal{H}_1)|\Psi\rangle = E|\Psi\rangle$$

$$|\Psi\rangle = |0\rangle + \underbrace{\sum_{n\neq 0}|m\rangle\langle m|\Psi\rangle}_{|\Psi_1\rangle}$$

$$(E-\mathcal{H}_0)|\Psi\rangle = \mathcal{H}_1|\Psi\rangle$$

$$\langle m|E-\mathcal{H}_0|\Psi\rangle = \langle m|\mathcal{H}_1|\Psi\rangle$$

$$(E-E_m)\langle m|\Psi\rangle = \langle m|\mathcal{H}_1|\Psi\rangle$$

$$\langle m|\Psi\rangle = \frac{\langle m|\mathcal{H}_1|\Psi\rangle}{E-E_m}$$

Van Vleck.

$$2\sum_{m\neq 0}\frac{\langle 0|\mathcal{H}_1|m\rangle\langle m|\mathcal{H}_1|0\rangle}{E_0-E_m} = \text{correction d'ordre } B^2$$

$$\Delta E = -|a|B^2 \qquad M = -\frac{\partial E}{\partial B} \qquad \chi = \frac{\partial M}{\partial H}$$

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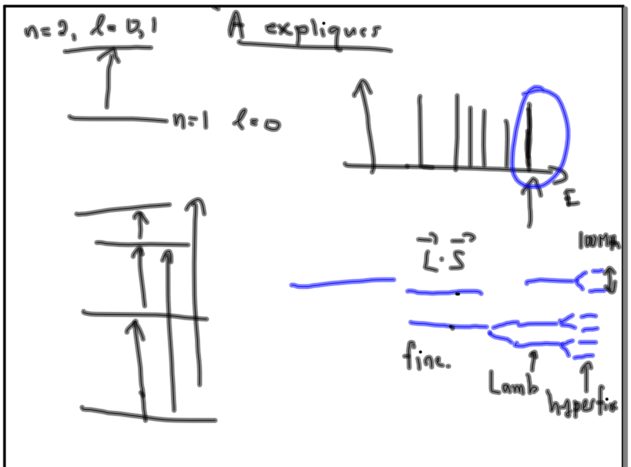

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2.6 Structure fine, hyperfine + Lamb.

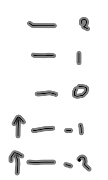
Règles de Hund 3d $l=2$

1) Choisir $\vec S$ maximum

2) Choisir $\vec L$ maximum

3) $J = L-S$ si moins que demi-remplie.

$J = L+S$ si plus que demi-rempli



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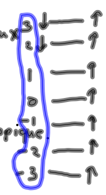
Dy^{3+} 4f $l=3$

7 niveaux

9 électrons

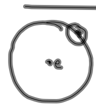
Notation spectroscopique



$l=$ 0	1	2	3	4
S	P	D	F	G

5	6	7
H	I	

$${}^{2S+1}L_J \longrightarrow \boxed{{}^6H_{15/2}}$$



$$\vec B = \frac{\vec E\times\vec v}{c^2} \qquad \vec E = -\frac{\vec r}{r}\vec\nabla V$$

$$E = -\frac{1}{2}\vec m\cdot\vec B$$

$$\vec m = -\mu_B g\vec S$$

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