* اختلال مستقل از زمان :

$$W = e\varepsilon \begin{pmatrix} \langle 200|z|200\rangle & \langle 200|z|211\rangle & \langle 200|z|21,0\rangle & \langle 200|z|21-1\rangle \\ \langle 211|z|200\rangle & & & \\ & & & \\ & & & \langle 21-1|z|21-1\rangle \end{pmatrix}$$

$$|n\,l\,m_l\rangle = |200\rangle,\ |21,-1\rangle,\ |210\rangle,\ |21,1\rangle \qquad E_2^0 = -\frac{13.6\,eV}{4} \rightarrow \text{تبهگنی ۴ گانه}$$

$$H_p = \underbrace{e}_{\text{بار الکتریکی}}\ \underbrace{\varepsilon}_{\text{میدان الکتریکی}}\ z \qquad \langle 100|z|100\rangle = 0 \qquad \begin{pmatrix} & \\ & \end{pmatrix}_{4\times 4}$$

$$\det\left(W_{\alpha\beta} - E_n^1\,\delta_{\alpha\beta}\right) = 0 \qquad \langle \phi_{n\alpha}|W|\phi_{n\beta}\rangle$$

$$H_0|\phi_{n\alpha}\rangle = E_n^0|\phi_{n\alpha}\rangle \qquad H = H_0 + H_p \rightarrow \lambda W$$

درجه تبهگنی

$$\alpha = 1, \ldots, 4 \qquad H|\psi_n\rangle = E_n|\psi_n\rangle$$

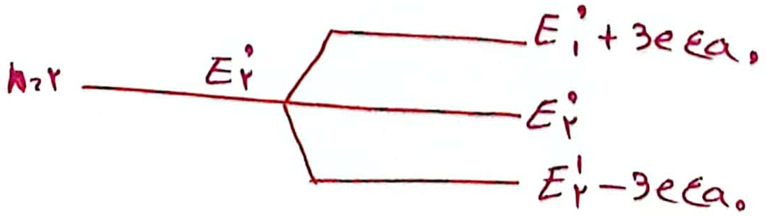
$$-3e\varepsilon a_0 \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$$

$$\begin{vmatrix} -E' & -3e\varepsilon a_0 \\ -3e\varepsilon a_0 & -E' \end{vmatrix} = (E')^2 - (3e\varepsilon a_0)^2 = 0 \Rightarrow E' = \pm 3e\varepsilon a_0$$

$$E_2^1 = 0 \qquad E_2^1 = 0 \qquad E_2^1 = -3e\varepsilon a_0 \qquad E_2^1 = 3e\varepsilon a_0$$

$$|\psi_2\rangle_1 = \frac{1}{\sqrt{2}}\left(|200\rangle + |210\rangle\right) \qquad |\psi_2\rangle_2 = \frac{1}{\sqrt{2}}\left(|200\rangle - |210\rangle\right)$$

$$|\psi_2\rangle_3 = |21,1\rangle \qquad |\psi_2\rangle_4 = |21,-1\rangle$$



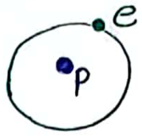
جفت شدگی اسپین-مدار:

-میدان الکتریکی با دو قطبی الکتریکی و میدان مغناطیسی با دو قطبی مغناطیسی برهم کنش می کنند.

$$\mu_s = -\frac{e}{m_e c}\,\vec{S} \longrightarrow \text{اسپین}$$

μ_s ← گشتاور دوقطبی مغناطیسی

m_e ← جرم الکترون



$$V = -e\Phi$$

$$\vec{B} = -\frac{1}{c}\vec{v}\times\vec{E} = -\frac{1}{m_e c}\vec{P}\times\vec{E} = \frac{1}{m_e c}\vec{E}\times\vec{P} = \frac{1}{e m_e c}\frac{1}{r}\frac{dV}{dr}\,r\times P =$$

گشتاور الکترون ←

$$\frac{1}{m_e c}\frac{1}{r}\frac{dV}{dr}\vec{L}$$

گشتاور زاویه ای مداری ←

$$E = -\nabla\phi = \frac{1}{e}\frac{\vec{r}}{r}\frac{dV}{dr}$$

پتانسیل الکتریکی ←

$$H_{SO} = \frac{1}{m_e^2 c^2}\frac{1}{r}\frac{dV}{dr}\vec{S}\cdot\vec{L} = \frac{e^2}{2 m_e^2 c^2}\frac{1}{r^3}\vec{S}\cdot\vec{L} \qquad V = \frac{-e^2}{r}$$

H_{SO}: هامیلتونی اختلالی

2 ← اثر توماس

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

* حالت پایه اتم هیدروژن:

$$|n\,l\,j\,m_j\rangle \leftarrow |n\,l\,m_l\,m_s\rangle$$

$$J^2 = L^2 + S^2 + 2\vec{S}\cdot\vec{L} \Rightarrow S\cdot L = \frac{1}{2}(J^2 - L^2 - S^2)$$

$$\psi_{nlm} = R_{nl}(r)\,Y_{lm}(\theta,\varphi)$$

$$|l \pm \tfrac{1}{2}\, m\rangle = \sqrt{\frac{l \mp m + \frac{1}{2}}{2l+1}}\,\left|l, \tfrac{1}{2}; m+\tfrac{1}{2}, -\tfrac{1}{2}\right\rangle \pm \sqrt{\frac{l \pm m + \frac{1}{2}}{2l+1}}\,\left|l, \tfrac{1}{2}, m-\tfrac{1}{2}, \tfrac{1}{2}\right\rangle$$

$$\psi_{n,l,\underbrace{l\pm\frac{1}{2}}_{j},m}(r,\theta,\varphi) = R_{nl}(r)\left[\sqrt{\frac{l\mp m+\frac{1}{2}}{2l+1}}\,Y_{l,m+\frac{1}{2}}(\theta,\varphi)\left(\tfrac{1}{2}, -\tfrac{1}{2}\right) \pm\right.$$

$$\sqrt{\frac{L\pm m+\frac{1}{2}}{2L+1}}\; Y_{L,m-\frac{1}{2}}(\theta,R)\,|\tfrac{1}{2},\tfrac{1}{2}\rangle\Big]$$

(1)

$$E_{n,so}=\langle n,L,L\pm\tfrac{1}{2},m|H_{so}|n,L,L,\pm\tfrac{1}{2},m\rangle=\frac{e^2}{4m_e^2c^2}\underbrace{\langle nr|\frac{1}{r^3}|n\ell\rangle\hbar^2}$$

$$(\delta(\delta+1)-L(L+1)-\tfrac{3}{4})$$

$$\frac{2}{\hbar^3 L(L+1)(2L+1)a_0^3}$$

$$E^{(1)}_{so}=\frac{\alpha^4 m_e c^2}{2n^3}\left[\frac{\delta(\delta+1)-L(L+1)-\frac{3}{4}}{L(L+1)(2L+1)}\right] \qquad \alpha=\frac{\hbar^2}{m_e c a_0}=\frac{1}{137}$$

در $L=0 \leftarrow$ جداشدگی فوق ریز داریم hyper Line spliting

$$E_n=-\frac{\alpha^2}{n^2}$$

* تصحیح نسبیتی:

$$E=\frac{p^2}{2m}+V \qquad E=\sqrt{p^2c^2+m^2c^4}$$

$$\rightarrow \frac{1}{2}mv^2$$

کلاسیکی (غیر نسبیتی)

$$E=\sqrt{p^2c^2+m_0^2c^4}\Rightarrow T=E-E_0=\sqrt{p^2c^2+E_0^2}-E_0=$$

$$E_0\left(\frac{p^2c^2}{E_0^2}+1\right)^{1/2}-E_0=E_0\left(1+\frac{p^2c^2}{2E_0^2}-\left(\frac{p^2c^2}{E_0^2}\right)^2\frac{1}{8}+\cdots\right)-E_0=$$

$$=\frac{p^2}{2m_0}-\frac{p^4}{8m_0^3c^2}$$

H_R

$$\delta=L\pm\frac{1}{2} \qquad L=\delta\mp\frac{1}{2}$$

$$E'_R=\langle nLJm_J|-\frac{1}{8m_0^3c^2}p^4|nL\delta|n\delta\rangle=-\frac{\alpha^4 m_e c^2}{8n^4}\left(\frac{8n}{2L+1}-3\right)$$

$$E'_{\text{دلخواه}}=E'_{so}+E'_R=\frac{\alpha^4 m_0 c^2}{2n^3}\left[\frac{\delta(\theta+1)-L(L+1)-3/4}{L(L+1)(2L+1)}-\frac{1}{4n}\left(\frac{8n}{2L+1}-3\right)\right]$$

$$E'_{\text{دلخواه}}=\frac{\alpha^4 m_e c^2}{8n^4}\left(3-\frac{4n}{\delta+\frac{1}{2}}\right)$$